DIAGNOSTICS OF PERIPHERAL MILLING PROCESS USING METHODS OF TIME SERIES ANALYSIS

by

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CERTIFICATE

28.1.99

It is certified that the work contained in this thesis, entitled " **Diagnostics of a Peripheral Milling Process Using Methods of Time Series Analysis**", by *Kanu Tripathi*, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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A C K N O W L E D G E M E N T

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A B S T R A C T

The present work deals with the problem of on-line monitoring and diagnosis of a peripheral milling process. It provides a foundation for an approach of development for a microprocessor-based diagnostic system of such a machining operation. The diagnostic procedure consists of measurements of the vibrations of workpiece by an accelerometer and numerical processing of these data. Usefulness of this approach has been demonstrated with the help of theoretical considerations regarding machine tool diagnosis as well as experimental investigations. A simple and computationally inexpensive algorithm has been effectively used to reveal the feature of eccentricity in the rotation of a cutter. Effectiveness and reliability of the fault identification is ensured by synchronizing of data with the rotation of the cutter and by providing fast numerical filtering procedures. It is shown that combination of data analysis in time and frequency domains gives good result for estimation of the state of the machining process. Different changes in the parameters of a machine tool dynamic system can be sensed and can be shown to be related to different causes or faults. In the present work, the vibratory motion of the workpiece has been sensed for diagnosing the presence of any eccentricity in the cutter with respect to its arbor. A technique for revealing of different faults based on sensing of non-uniformities in the data signals has also been discussed.

C O N T E N T S

Nomenclature

R	= cutter radius,
D	= cutter diameter,
t_m	= maximum undeformed chip thickness,
d	= depth of cut,
f_t	= feed per tooth,
t_{avg}	= average undeformed chip thickness,
$\underset{\sim}{y}(t)$	= time dependent vector of state of a process,
$y_1(t),\ y_2(t), \ldots, y_k(t)$	= elements of vector $\underset{\sim}{y}(t)$,
$\underset{\sim}{z}(t)$	= time dependent vector of quality of a process,
$z_1(t),\ z_2(t), \ldots, z_l(t)$	= elements of vector $\underset{\sim}{z}(t)$
Y	= set of all feasible states of a cutting process,
Z	= set of prescribed quality of output of a process,
$\underset{\sim}{x}(t)$	= vector of measurable parameters characterizing a machining process,
G_y $\cdot G_z$	= operators, transforming Y and Z into the $x(t)$-domain,
X_y, X_z	= transformed sets Y and Z in the $x(t)$-domain,
X_{F1}, X_{F2}, X_{Fi}, $X_{Fj}, \ldots,$ X_{Fn}	= values of vector $x(t)$ in case of faults #1, #2, #i, #j, ..., #n,
$H(z)$	= linear filter
$A(z)$ and $B(z)$	= polynomials
$w(n)$	= white noise sequence
$x(n)$	= random process sequence

a_k and b_k	= filter coefficients
$Z(t) = Z_1, Z_2, \ldots Z_t$	= a time series
$A_1, A_2, \ldots, A_t$	= noise components in $Z_2, \ldots Z_{t+1}$
$\phi_1, \phi_2, \ldots \phi_p$	= coefficeints of previous observations in autoregressive process
$\theta_1, \theta_2, \ldots \theta_q$	= coefficeints of A_t in moving average process
$\imath$	= $\sqrt{(-1)}$
ω	= frequency
$Z(\omega)$	= Fourier transform of a continuous function $z(t)$
Z_k	= discrete Fourier transform of discrete sequence z_r
B	= backward shift operator
x	= vector $\underset{\sim}{x}(t)$ reduced to a scalar (vertical vibrations of workpiece in the present case)
i	= index, denoting a particular number of revolution,
I	= total number of revolutions,
j	= index, denoting a particular number of element in a rotation,
J	= total number of the elements in a rotation,
x_j^E	= envelop curve for signal x (signal x, processed with Eqn 4.2),
x_{ij}	= value of signal x at jth element of ith revolution,
k, l, m, p, q, r, k, N	= any integer
$\bar{x}_k$	= kth element of the Moving Average

series (signal processed with Eqn. 4.3),

$\bar{T}_E$: envelop curve for processed signal $\bar{T}_i$

L I S T OF F I G U R E S

LIST OF TABLES

Chapter 1

Introduction

1.1 Development of Manufacturing Science

The basic manufacturing operations, which are carried out on the raw material to make a desired product, can be listed briefly as follows :

1. Refining and general preparation of the raw material.
2. Shaping of the material, which includes
    - Casting,
    - Forming by plastic deformation and shear cutting,
    - Machining etc.
3. Fabrication, welding , adhesive bonding etc.
4. Assembly.
5. Cleaning, polishing, plating, painting, packaging etc.

Each of the above-listed operations has some physical phenomenon behind it which governs the different aspects of the operation. The necessity to understand the physics has arisen because of the greater requirements of controls to carry out the operations economically and to give better quality of the final product. This driving force has motivated engineers to develop the science of manufacturing.

Today, manufacturing science has several disciplines in which research is going on for improving the quality of a manufactured product. Some of these disciplines may be listed as follows:

(a) Study of Cutting Processes

This includes the study of chip formation, mechanics in various cutting operations and different work materials, tool life prediction, diagnosis of processes etc [1].

(b) Design

This includes designing of various cutting tools fixtures and other machine parts.[2]

(c) Study of Electro Physical and Electro Chemical Processes

This includes research in Electro-Discharge Machining, Ultra-Sonic Machining, Laser Beam Machining, Electron Beam Machining etc [3].

(d) Study of Forming Processes

This covers simulation of various extrusion and drawing processes, diagnosis and experimental investigation of various aspects of forming etc [4].

(e) Study of Abrasive Processes

This includes research in grinding and other abrasive processes [5].

(f) Machine tools

This includes study design and development of different machine tools e.g. lathes, milling machines, presses, shapers, grinders etc.

(h) Optimization of manufacturing systems

This includes the study of automation, flexible manufacturing systems, computer integrated manufacturing etc [6].

As the need of manufacturing different kinds of workpieces is growing day by day, it has become essential to find better methods to control the machine tool. Thus development of effective control strategies is an important area of research. The present work deals in this research area only.

1.2 Control and Diagnostics of a Machining Process

A block diagram of a typical machine tool is given in Fig.1.1.

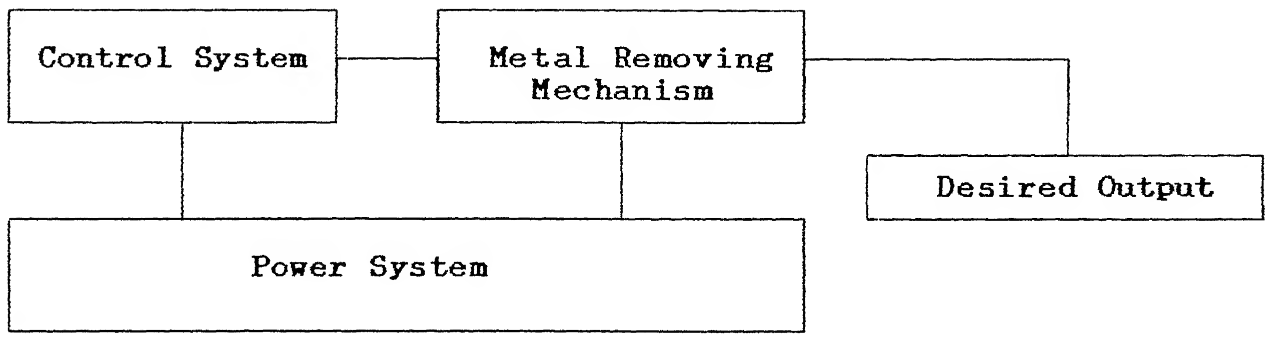


Fig.1.1 Block Diagram of a Typical Machine Tool

Any machine tool necessarily has a power system for the cutter and different feeding mechanisms etc. The tool also has a control system which may be defined as the control of machining process with a feedback device to allow for performance of an ordered sequence of events. This basically sets the different cutting parameters e.g. speed of cutter, different feeding rates, depth of cut, positional parameters, change-over from one set of conditions to another set, checks for safety of the operator etc. The third part of the machine tool is the metal removing mechanism which enables the machine tool to carry out the machining operation.

Since the machining operation has several constraints on different cutting parameters, requirement of the control system becomes necessary. For example, the depth of cut should not be more than a particular limit to avoid accidents and also it should not be very less to achieve higher production rate. Similarly, the feeds in different directions should also be within a specified limit. Also, this limit changes from workpiece to workpiece, from cutter to cutter. Therefore, to perform the cutting operation efficiently, it is necessary to provide an appropriate control system.

Many times, in practice, some phenomena are encountered during machining which are unfavorable to the machining process. The examples of such phenomena may be failure of the key connecting the arbor with the cutter, cutter tooth/teeth failure, eccentric motion of cutter, teeth wear etc. In such cases, the operator of the machine takes necessary actions when such incidents are observed. In many cases, this may give rise to other accidents and thus may severely affect the production rate adversely. Because of not being able to observe continuously the smooth functioning of the machining process, the

control systems are not adequate in their present form.

In conventional manufacturing, the operator is not only responsible for basic activities of machining, e.g. loading and unloading parts and changing tools but also has to monitor the various aspects of the cutting process, such as tool wear, tool breakage, chip disposal, cutting temperature, surface finish, machine chatter, part dimensions etc. If some of these monitoring functions can be carried out automatically, the burden on the operator and the risk of human error will be reduced. Studies have shown that tool failure contributes, on an average, up to 6.8% to the downtime of machining centers [7]. An essential part of the machining system in the "unmanned factory", is the ability to change tools automatically due to excessive wear or other damage. Tool change/resharpening strategies, generally practiced on shop floors, are mostly based on the most conservative estimates of tool life from past experience. These approaches do not allow for tool breakage or chipping of the cutting edge as these are generally catastrophic situations. Hence, tools are generally underutilised. In an "unmanned factory", this has the effect of increased frequency of tool change and therefore increased cost. Hence, the need to observe cutting process automatically is further established. The present trends of manufacturing are emphasizing automation which includes developing methods to fully control the machining process [8]

The sensing of some parameters and actuating a feedback mechanism so as to ensure an acceptable level of performance of a machining process is known as Diagnostics of a machining process [9]. This includes sensing different aspects associated with a cutting process and giving different corresponding signals. The diagnostic system is

different from the control system in a sense that a diagnostic system includes the observation of the symptoms and inferencing from these observations about the status of the machining process. The control system, on the other hand, includes manipulation of the hardware based on the inferences reached by the diagnostic system.

Diagnostics of a system essentially involves three aspects, namely, theoretical, experimental and computational. The diagnostic system has to be based on some well-studied physical phenomena which has a direct relationship with the machining process. Physics of the phenomena determines the conditions of the physical quantities associated with the proper and improper machining. The experimental part of the diagnostic system includes the verification of the theoretical aspect and calibration of the system. The computational part of the diagnostic system is responsible for the processing of the sensed signal. All computations are performed using a suitable algorithm and the final inference is sent to the control system.

A diagnostic system should have the following features:

(a) Reliability, on the safe side.

- 100% indication on damage beyond a certain level.
- Minimum of false indications.

(b) Highly automated threshold setting.

- Independent of the cutting parameters.

(c) Robustness

- Highly sensitive to tool failures and other faults.
- Very low sensitivity to cutting transients (entry, exit, interrupted cutting) and to variation in cutting parameters.

(d) Practicality of the sensors

- Easy to locate in the machine,
- Applicability to high-speed machining.

(e)Fast response

- e.g. within one revolution of the first indication.

1.3 Literature Survey

Many researchers have worked in the field of machine tool diagnostics to sense different aspects of the cutting process and developed algorithms to identify the cutting state. The following is a brief survey of their work.

Li, Dan and Mathew [7] have provided a review paper on numerous techniques and methods for monitoring tool wear particularly in turning operations. The sensing is broadly classified into two major categories, namely, direct and indirect. Direct methods include direct measurement of the aspects of the cutting process while indirect methods include the measurement of the aspects of the cutting process through some other parameters associated with them. These are tabulated in Tab 1.1 and Tab 1.2. The author has summarized the pros and cons of all the procedures and has concluded that the direct methods cannot be used on shop floors because of either practical difficulties or low reliability.

Y. Altintas [12] has developed a time series model for on-line detection of tool failure for general milling. In this algorithm, the deterministic component is first separated and then the remaining force signal is tracked by an Auto-Regressive model of order one. The filter allows separation of cutting transients from tool breakage. Similar work has been done by Tlusty and Tarng [10]. They have presented a method based on pattern change recognition of the cutting

Table 1.1 Direct Methods Used for Diagnostics

Procedure	Measurement	Transducer
Optical	Shape or position of cutting edge	TV camera,optical transducer
Wear particles	Particle size and concentration	Spectrophotometer, scintillator.
Tool-work resistance.	Changes in junction resistance	Voltmeter.
Workpiece size	dimension of work piece	Micrometer, optical, pneumatic, ultrasonic, electromagnetic transducer.
Tool-work distance	distance of work piece and tool holder.	Micrometer, pneumatic gauge.

Table 1.2 Indirect Methods Used for Diagnostics

Procedure	Measurement	Transducer
Cutting force	Difference in cutting force.	Dynamometer, strain gauge
Acoustic emission.	Stress wave energy.	Acoustic emission transducer.
Sound.	Acoustic waves.	Microphone.
Vibration.	Vibration of tools and tool post.	Accelerometer.
Temperature.	Variation in cutting temperature of tool.	Thermometer, pyrometer.
Power input.	Power and current consumption of spindle or feed motor.	Ammeter, dynamometer.
Roughness of machined surface.	Changes in surface roughness of machined surface.	Mechanical stylus, optical transducer.

force signal. In their algorithm, regular periodic force component was filtered out and the change in signal due to broken tooth could be detected clearly. This is then measured and indicated. Danai and Ulsoy et al [13] have shown clearly the dependence of force variation on tool wear in turning. Similarly, Takata and Ahn et al [14] have described a monitoring method for multi-edge tool by means of fluctuation of a signal of spindle rotational speed. In their work, dependence of rotational speed of the spindle with the cutting operation is studied and used to isolate tool breakage. Mannan and Broms [15] have carried out a study to establish the feasibility of motor power and current measurements for diagnostic purpose and have concluded that detection of tool breakage using motor related parameters is possible. Hayashi and Thomas et al [16] have shown the possibility of using ultrasonic vibrations to detect tool breakage. Liang and Dornfeld have proposed a way to detect tool wear using acoustic emission [17].

Out of these several methods suggested by researchers, most have some or other limitations. Lee and Thomas et al [18] have stated in their review paper that existing monitoring devices for cutting forces need improvements to become efficient and durable enough for a manufacturing environment. Many times the cutting environment itself is hostile to sensors. Remote sensors are generally complicated and unable to distinguish the component of cutting forces and the force necessary to move machine parts. The power sensing methods have limitations because the power monitoring systems are strongly influenced by the friction and system inertia. The rotational speed sensing method also have limitation as the mechanical inertia of the machine parts acts as low pass filters. The vibration signal and

acoustic emission have been found to be the most suitable for the cutting operation diagnosis in almost all types of conventional metal removal processes.

1.4 Goals and Limitations of the Present Work

The present work proposes a way to detect eccentricity in the cutter in peripheral milling by on-line digital processing of the workpiece vibration signal to illustrate diagnostics of a milling process. The vertical vibrations of the workpiece have been sensed with a piezo-electric accelerometer. This signal is then recorded and digitized. After this, the data has been processed with an algorithm to indicate the presence of eccentricity in the motion of the cutter and to differentiate the regimes of high and low metal removal rates. The algorithm also identifies non-cutting regime, if present, by comparing the data of idle running of the machine with the data while the machine is cutting.

The present thesis has been organized in the following way. The fundamentals of milling process have been covered in Chapter 2. This includes the theory and geometry of the milling process and different breakdowns associated with the process. Chapter 3 discusses the mathematical model of the milling process from the viewpoint of diagnostics of the process and describes the use of Time Series Analysis for diagnostic purpose. Chapter 4 covers the selection of measuring parameters, experimental set-up and data processing. Finally, discussions and conclusions are covered in Chapter 5.

Chapter 2

The Fundamentals of Milling Process

2.1 Introduction

As mentioned in the previous chapter, the research in diagnostics is going on for various manufacturing operations e.g. turning, milling, grinding etc. In the present work, diagnostics of a peripheral milling process has been studied. The primary aim of this chapter is to discuss those aspects of the milling process which influence the diagnostics of the process. These aspects are generally related to the theory and geometry of the milling process. This is because the signals used for the diagnostic purpose are generated by the cutting process which depends on the theory and geometry of the process. The common faults as observed in a typical milling shopfloor are also of importance from the point of view of diagnostics of the process. The reason is that these faults need to be indicated by the diagnostic system as and when observed. This can be done only when these faults are well studied. These common faults are also covered in this chapter. The reasons for selecting eccentricity for the present work have been discussed at the last.

2.2 Milling Process

Milling is a machining process whereby a surface is generated with a rotating toothed cutter. Each tooth takes an individual chip. The surface generated may be either a plane or a curved surface. Furthermore, a milling process can also generate profiles such as thread, cam profile, etc.

In order to provide feed, the relative motion between cutter and

a work piece must be well defined. In most applications of milling, the cutter revolves about a stationary axis at relatively high speed, and work is moved past the cutter (with suitable depth of cut) at a comparatively low rate of feed. In other cases, the work piece may revolve slowly, as in thread milling, while the cutter revolves at high speed.

Types of Milling

Broadly, the milling process can be divided in two types, namely, peripheral and face milling. In peripheral milling, the surface is generated by teeth located on the periphery of the cutter body. The surface may be flat or profiled. In face milling, the milled surface is generally at right angles to the cutter axis. The generated surface is flat and is produced by the combined action of the cutting edges on the face of the cutter as well as its periphery.

In peripheral milling, the work piece can be fed either with or against the direction of the cutter rotation. When the cutter rotates in the feed direction, the method is termed as in-cut/climb/down milling. Here each tooth cuts inwards starting from unmachined surface of the work piece and finishes at the machined surface. On the other hand, when the cutter rotates against the direction of feed the method is called out-cut/conventional/up milling. The tooth movement in this case is opposite to that of down milling i.e. the cutting starts from the finished surface and ends at original surface (Fig.2.1). Since down milling has a tendency of dragging the job into the cutter, up milling is safer and commonly done. However, down milling results in better surface finish and longer tool life.

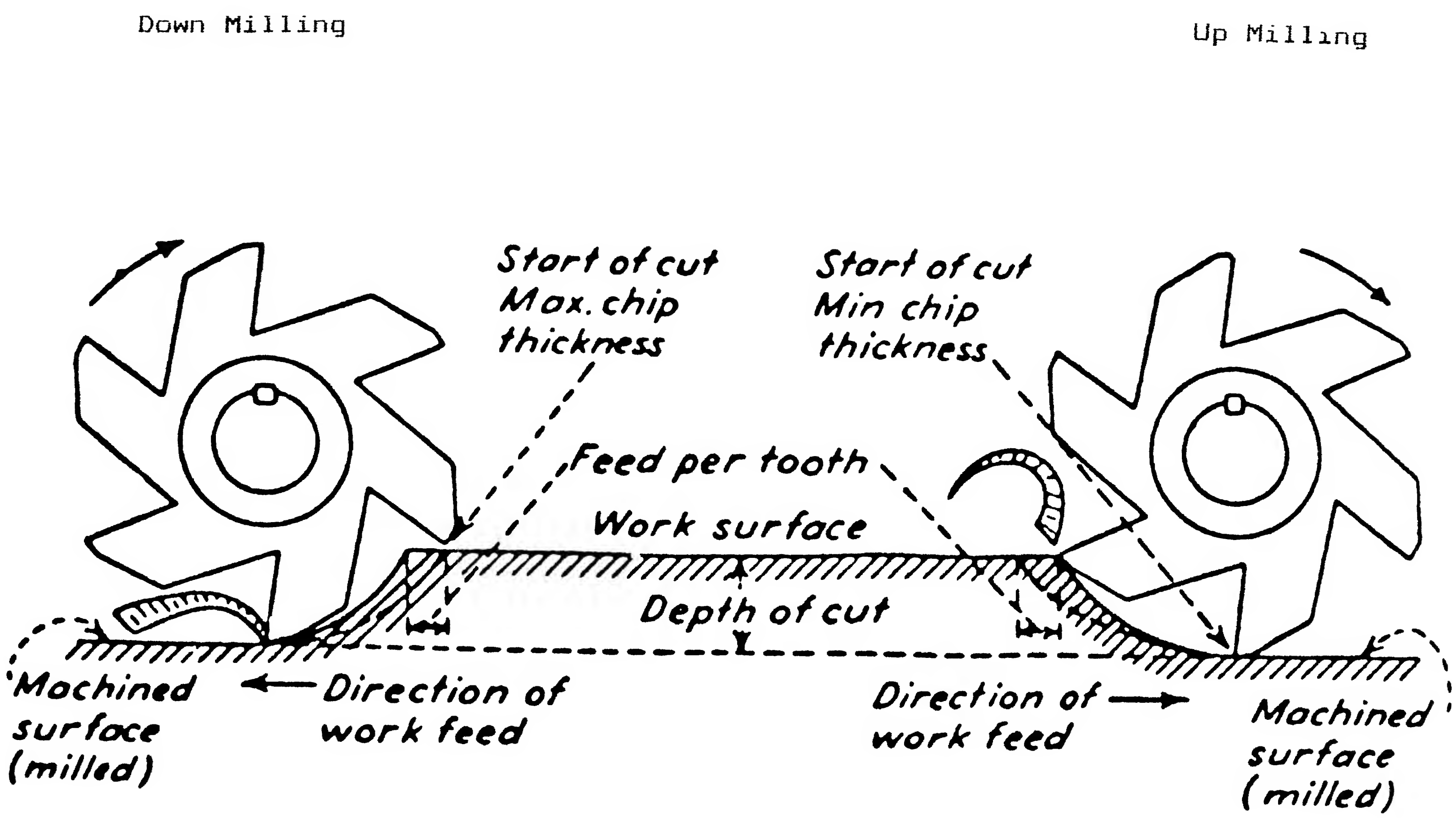


Fig.2.1 Down and Up Milling

Milling Cutters

A milling cutter is a multi-point rotary cutting tool provided with one or more cutting elements called teeth, which intermittently engage the work piece and remove material by relative movement of workpiece and cutter. Typical milling cutters and their applications are shown in Fig.2.2. Because of diverse shapes and applications, many types of classifications of milling cutters have been proposed e.g. classification based on construction, on relief of tooth, on the purpose of process, on method of mounting etc [19].

Tooth Parts and Angles

As mentioned above, many kinds of cutters are in use for different applications. Since experiments have been done using a side milling cutter, description of side milling cutter is given here. A side milling cutter (Fig.2.3) has teeth on the cylindrical surface or the periphery and on the face of the cutter. The distance between the two ends of the edge of the tooth is called the cutter width if small or cutter length if long compared with respect to the diameter of the cutter.

Land

The part of the surface adjacent to the cutting edge on the outer side of the tooth is called the land. (Fig.2.3)

Relief Angle

The relief angle (peripheral) is the angle between the surface formed by the land and the tangent to the cutter outside circle passing through the cutting edge in the diametrical plane. (Fig.2.3)

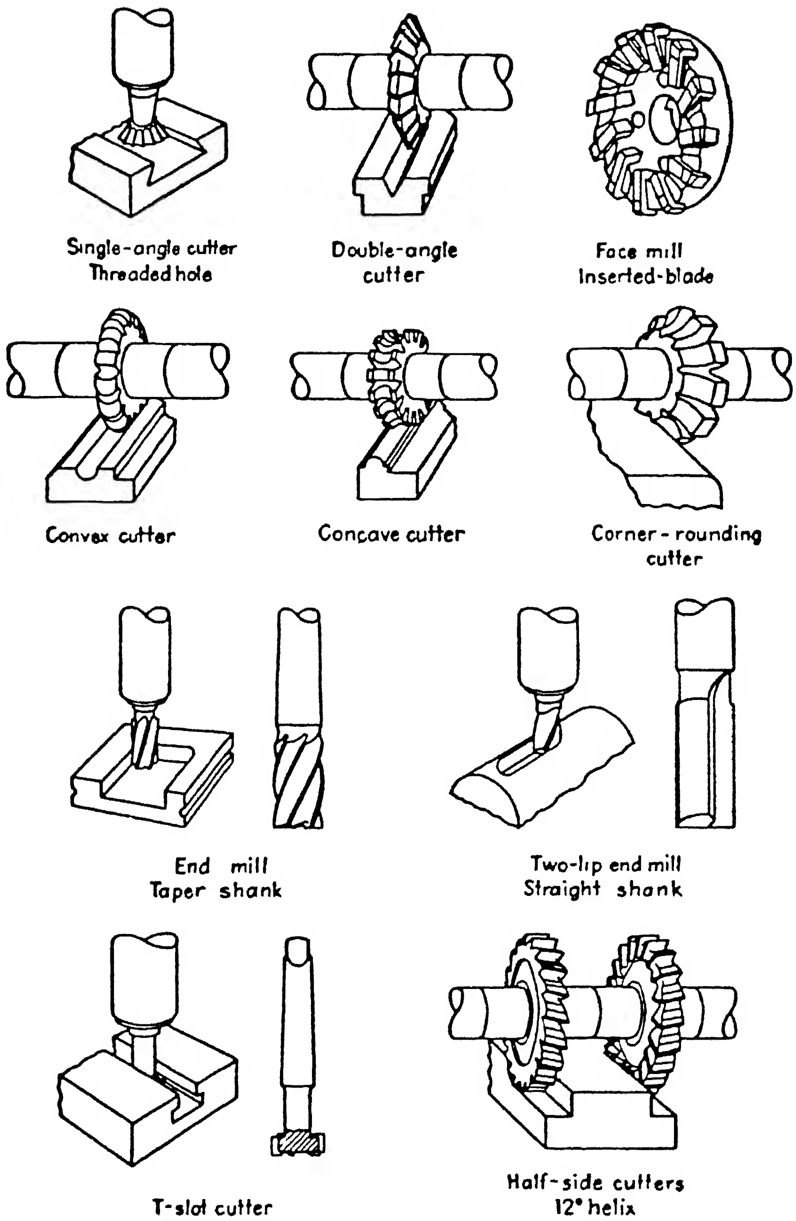


Fig.2.2 Some Milling Cutters and Their Applications

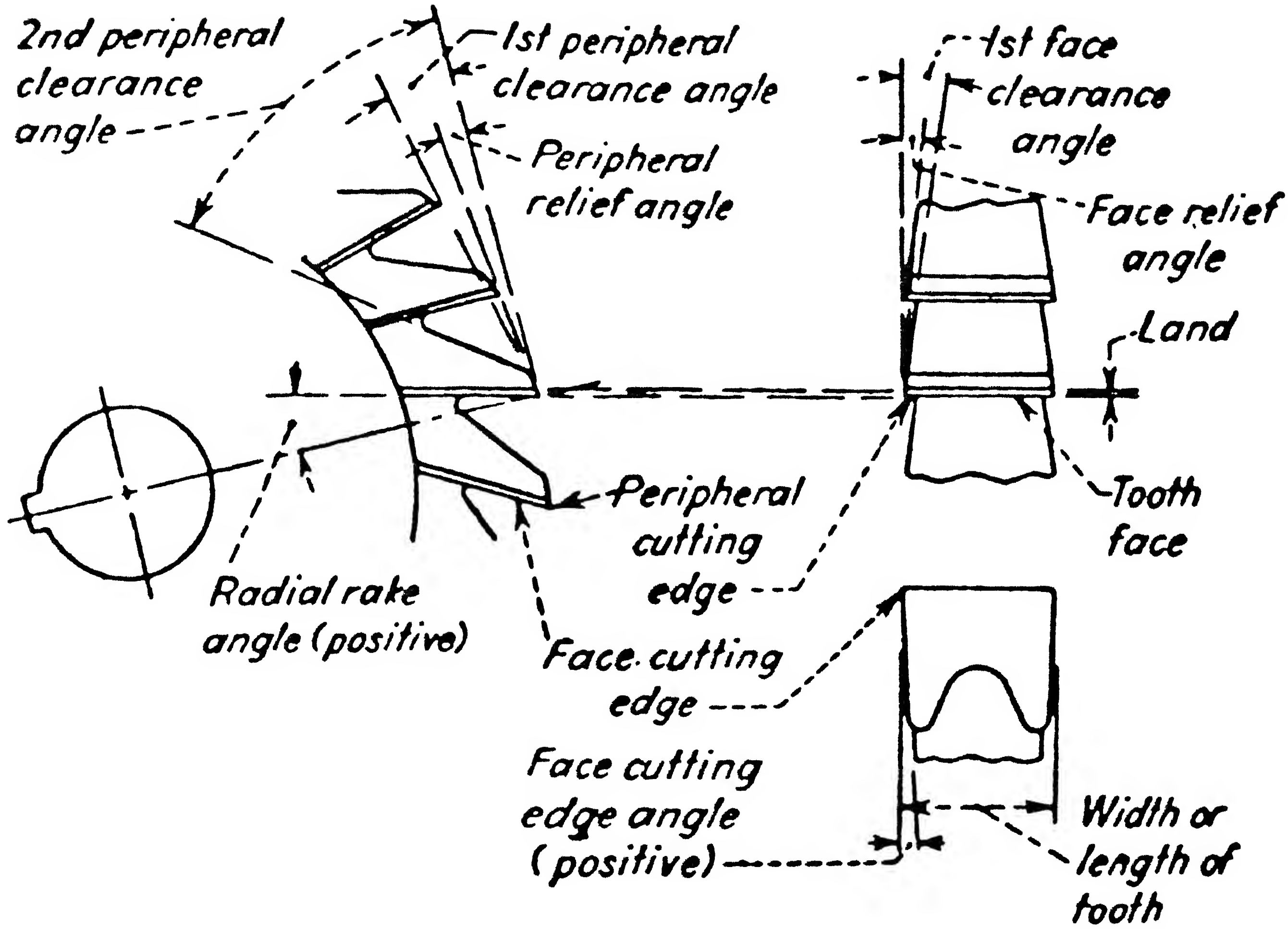


Fig.2.3 Nomenclature of a Side Milling Cutter

Clearance Angle

The clearance angle (peripheral) is the angle between the surface back of the land and a tangent passing through the cutting edge. The back of the tooth may be made up of single or double planes. The first clearance angle is the one made by the land and first back plane (adjacent to the land) and the second clearance angle is the one made by the second back plane and the land. (Fig.2.3)

Radial Rake Angle

The angle formed in the diametrical plane between the face of the tooth and a radial line through the cutting edge is called radial rake angle. (Fig.2.3)

Normal Rake Angle

The rake angle of the tooth face at right angles to the cutting edge is called normal rake angle. (Fig.2.3)

Lip Angle

Angle between the land and the face of the tooth is called lip angle. (Fig.2.3)

Most of the common milling cutters are provided with a standard central hole and a key way to mount the cutter on the arbor.

Geometry of a Peripheral Milling Process

Although the path of the milling cutter tooth is trochoidal, the following discussion assumes that the tooth path is circular. This is because of the practical impact of this assumption on the diagnostic

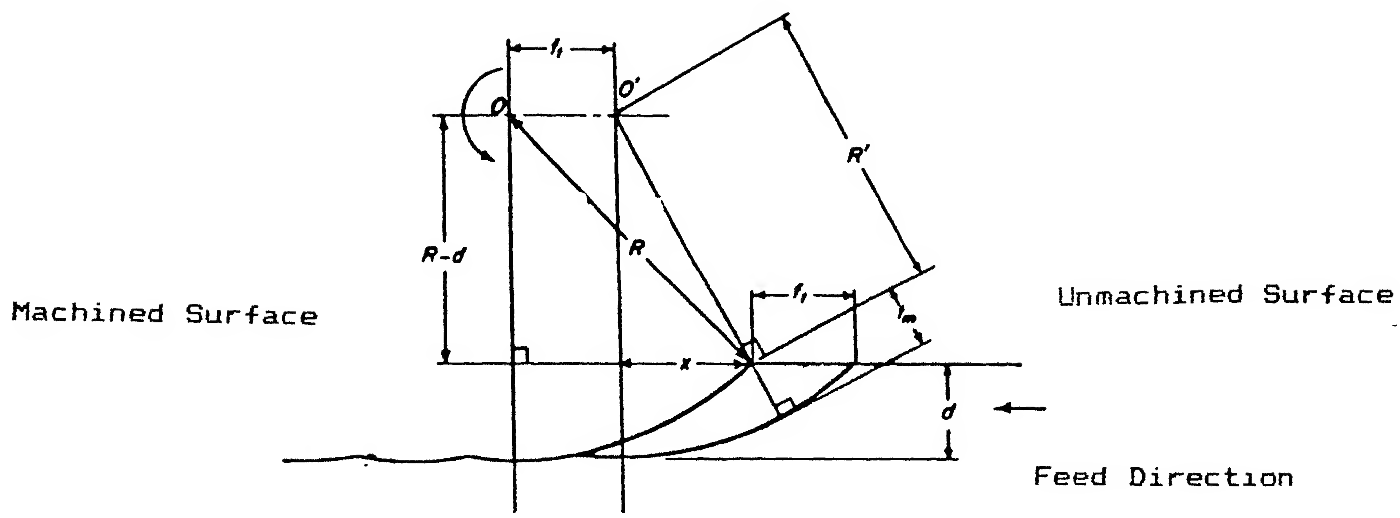


Fig.2.4 Geometry of Chip Thickness Variation in Up-Milling Process

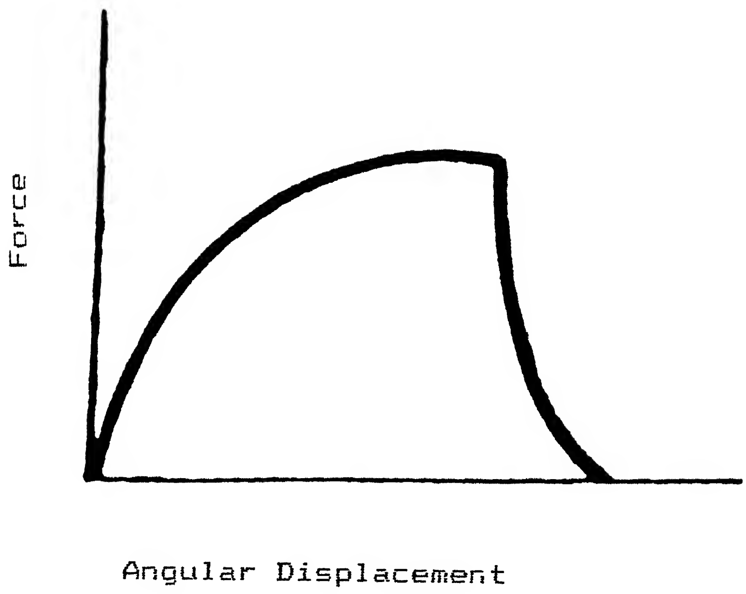
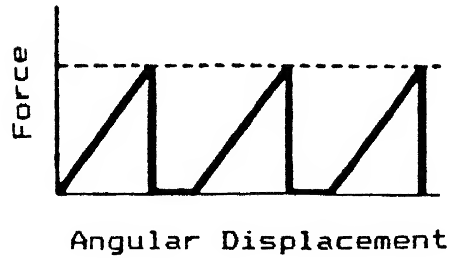
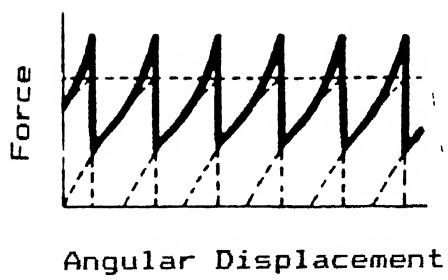


Fig.2.5 Cutting Force Variation in Up-Milling While Cutting With Single Tooth



(a) Cutting With Single Tooth at a Time



(b) Cutting With Multiple Teeth Simulteneously

Fig.2.6 Different Possible Cases of Cutting Force Variation in UP-Milling

study of the system is negligible while the mathematics involved in computation becomes simple. Figure 2.4 shows the variation of the thickness of the chip during the progress of the cutter tooth. The standard approximate results are given below [20].

$$t_m = 2 \cdot f_t \sqrt{[\ d/D \cdot (1 - d/D)\ ]} \tag{2.1}$$

$$L = D/2 \cdot \cos^{-1}(1 - 2 \cdot d/D) \tag{2.2}$$

$$t_{avg} = \frac{2 \cdot f_t \cdot d}{D \cdot \cos^{-1}(1 - 2 \cdot d/D)} \tag{2.3}$$

where, R = cutter radius,

D = cutter diameter,

t_m = maxim undeformed chip thickness,

d = depth of cut,

f_t = feed per tooth,

t_{avg} = average undeformed chip thickness.

It can be seen that during cutting by one tooth, the chip thickness varies. In up milling the force gradually builds up to a maximum value and then falls down rapidly (Fig 2.5). The relative value of the angle per tooth with respect to the angle subtended by the arc of cut at the centre gives two possibilities of cutting as shown in Fig. 2.6. In the first case, when only one tooth is involved in cutting at a time, the variation in force is very high and this gives rise to high vibrations. The second case arises when more than one tooth are cutting simultaneously. Here the highest value of force is higher than that in the first case but the operation is more smooth as the fluctuations in the force are less.

2.3 Common Faults in Milling Process

All cutting tools wear out during machining process. Also, the

continuous use of the machine tool gives rise to the wear of different machine parts. The machining characteristics of the cutter and different machine parts will give rise to one or more of the following faults as wear progresses [21].

Abrasion

All work materials abrade or wear the cutting edges. The friction or the rubbing action which takes place as the cutter teeth rotate in the cut, continuously wears away some amount of cutting edges. This dulls the keen cutting edge and produce a wear land. The greater the wear land, the more force is required to make the cutting edge penetrate the work and more heat is produced. These elements produce further abrasion. If the cutter is not resharpened in time, the cutting edge may finally disintegrate.

Chipping of Edge

This condition occurs when the cutting edge is thin and weak from excessive relief and rake angles or the tool material is too brittle. In some cases, abrasion conceals chipping and it is difficult to find the real cause of the cutter wear.

Built-Up Edge

This is the welding of a portion of chip to the cutting edge or the cutting face adjacent to the cutting edge. It is the result of the heat and pressure existing in the cutting zone. If the built-up edge becomes large, it may actually function as a new irregular cutting edge which may periodically break loose from the tool. This can cause a rough surface or a chipped cutting edge.

Cratering

This is the wearing of crater in the tooth face back from the cutting edge. As the crater grows and approaches the cutting edge, it may cause chipping.

Overheating of Cutting Edges

This is caused by the higher friction and results in faster abrasion.

Cutter Breakage

This occurs when the tool is subjected to stresses higher than that it can withstand. This may result because of hardness of work material, high chip load per tooth, backlash or impact when climb milling or a poor machine and fixture set up.

Key Failure

The key, used to give positive motion to the cutter through the arbor, may shear if the shear force on it crosses a prescribed limit. The cutter stops cutting as the key fails and if the feed motions are not stopped immediately, there may be a severe damage to the machine tool.

Eccentricity in Cutter Rotation

When the centre of the cutter rotates about an axis with a finite radius, the cutter rotation is called eccentric. This results in bad surface roughness and increased chances of teeth failure.

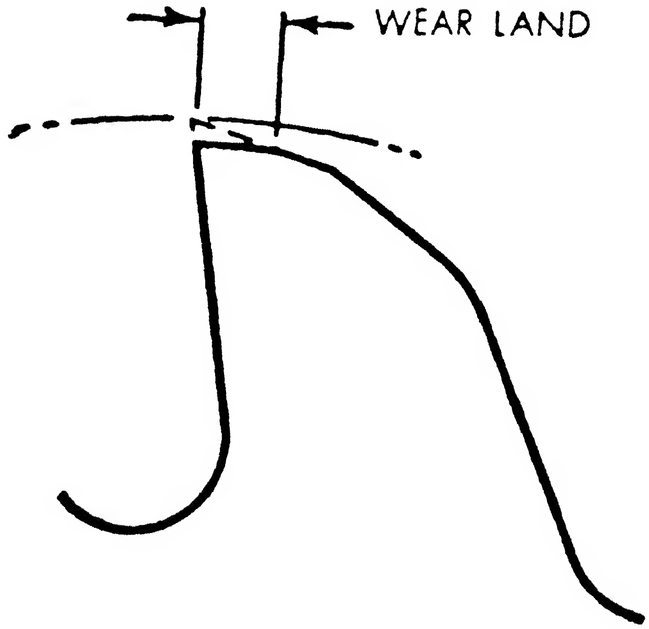


Fig.2.7 Wear Land

Because of these several different kinds of cutter breakdowns and other faults, it is a general practice on the shop floor to establish definite schedules for sharpening tools to obtain better results. Some of these norms are as follows:

(a) Sharpen at a predetermined wear land value.

Cutter should be sharpened as soon as the wear land (Fig 2.7) reaches a predetermined value. This method is used on production runs where uneven amounts of stock is removed or where the material varies in machinability.

(b) Sharpen after predetermined period of use.

(c) Sharpen when the product quality indicates a deterioration.

(d) Sharpen when the power increases.

As mentioned in the last chapter, eccentricity has been chosen for study in the present work. The reasons for this have been discussed here briefly. Practically, eccentricity is an unavoidable feature of any milling machine. It can come into picture because of bad profile of arbor, wear of hanger bearing of the milling machine and bad geometry of the cutter. Eccentricity affects the surface finish adversely. Also, the load is unevenly distributed over the different teeth of an eccentric cutter which increases the possibility of tooth failure. Furthermore, it becomes more difficult to detect other aspects of the milling process e.g. tooth breakage, key failure etc if the eccentricity is present. This is because of the superimposition of the signal generated due to the eccentricity and other aspects of the process. Therefore, the need to investigate and understand the effect of eccentricity on the vibration signal is evident for diagnostic study of a milling process.

Chapter 3

Use of Time Series Analysis for Diagnostics

3.1 System Model

A machining process can be characterized for diagnostic purpose by the time dependent vectors of the process state $\underset{\sim}{y}(t)$ and the process quality $\underset{\sim}{z}(t)$. The following parameters can be considered as elements of the vector $\underset{\sim}{y}(t)$:

- cutting speed,
- depth of cut,
- velocities of the formative motions,
- tool wear rate,
- rate of change of tool wear rate and
- cutting force etc.

The vector $\underset{\sim}{z}(t)$ any consist of:

- shape of a machined workpiece (roundness for turning, flatness for milling etc.),
- roughness of the machined surface,
- physical features of a machined workpiece (e.g. hardness etc.).

Dependence of vector $\underset{\sim}{z}(t)$ upon time means that these parameters are generated for different parts of workpiece at different instants of time. During the machining process, their characteristics could change. This could lead to differences in production quality parameters for different instants of the process. Suitable performance of a machining process can be achieved under the following conditions:

$$\begin{aligned} \underset{\sim}{y}(t) &= [y_1(t),\ y_2(t),\ldots,y_k(t)] \in \mathrm{Y} \\ \underset{\sim}{z}(t) &= [z(t),\ z(t),\ldots,z(t)] \in \mathrm{Z} \end{aligned} \qquad (3.1)$$

where Y is a convex set of all feasible states of the cutting process,

and Z is a convex set of the "prescribed" quality of the output of the process. The ultimate goal of a diagnostic system is to check the fulfillment of the conditions prescribed in Eqn. 3.1 and indicate their violation, if any. Besides this, an intelligent diagnostic system has

- to take appropriate actions in order to stop the machining process in case of violation of Eqn. 3.1 with minimum loss,
- to locate and indicate the fault and
- to predict/estimate current probability of occurrence of faults.

A diagnostic system could check fulfillment of the conditions stated in Eqn. 3.1 either through direct measurements elements of vectors $\underset{\sim}{y}(t)$ and $\underset{\sim}{z}(t)$ or by using an indirect data about these elements. Let us define vector $\underset{\sim}{x}(t)$ as a vector of measurable parameters characterizing a milling process. Following parameters may be considered as its elements: displacements, velocities, accelerations of various parts (e.g. spindle, carriage, bed etc.), electric current of the drive motors, power consumed during machining, acoustic emission from the cutting zone, electric resistance of the tool-workpiece contact etc. Sets Y and Z are transformed by operators G_y and G_z into convex sets X_y and X_z respectively in x-domain such that

$$X_y = G_y\{Y\} \qquad (3.2)$$
$$X_z = G_z\{Z\}$$

Now, if the performance of a machining process is such that it satisfies the following condition

$$\underset{\sim}{x}(t) \in [\, X_y \cap X_z \,] \qquad (3.3)$$

then conditions given in Eqn. 3.1 are also satisfied. Therefore, the machining process is running properly. It means that an option for a diagnostic to check the fulfillment of conditions given in Eqn. 3.1 is to check an equivalent condition given in Eqn 3.3. Elements of vector $\underset{\sim}{x}(t)$ are usually available for on-line monitoring in industrial conditions rather then elements of vectors $\underset{\sim}{y}(t)$ and $\underset{\sim}{z}(t)$. However, elements of vector $\underset{\sim}{x}(t)$ are often considerably contaminated by noise. Below, we refer to only such diagnostic systems which provide indirect monitoring and operate with elements of vector $\underset{\sim}{x}(t)$. Therefore, the changes in all measuring parameters are described in x-domain.

Another important aspect of machine tool diagnostics is to check the actual input signals for a machine tool. These are basically different logical signals (e.g. to change the tool) and voltage of drive motors controlling the formative motions as determined by CNC units. These voltages can be monitored relatively easily. In the present work, the problem of control of a machine tool i.e. synthesis of inputs according to a particular criterion, is not discussed. Here, we are interested only in keeping these inputs within certain limits to provide a proper machining process. So, the inputs are considered simply as elements of vector $\underset{\sim}{x}(t)$. The domain of their permitted values, in order to provide a proper cutting process and the prescribed quality of the process output, are added to the sets $\mathbf{X}_y$ and $\mathbf{X}_z$. Moreover, the x-domain can further be enhanced to include the inputs of machine tool also.

3.2 Introduction to Time Series Analysis

A time series is a random or non-deterministic function of an independent variable, time. The dependence of the function on time is

governed by probabilistic laws. Because of this the processing and description of a time series is different from that of a deterministic function. The analysis of a time series can be carried out in time domain and frequency domain. A time series can be thought of as being composed of sine waves of different amplitudes and frequencies. Description and analysis of a time series using these frequency components comes under the frequency domain analysis. The time domain analysis includes processing of the actual data itself. Following is a brief introduction to these different methods of time series analysis.

Analysis of a Time Series in Time Domain

A time series is called stationary of order one if the mean and variance of the series are constant. For the present case, only the analysis of stationary time series is of importance and has been discussed.

Filters

A filter is a transforming operator which, when applied on a time series, changes the series in a desirable manner. Some basic filters, used to process data, have been given in the following. The linear filter H(z) for generating the random sequence { x(n) } from the white noise sequence { w(n) } may be expressed as .

$$H(z) = \frac{B(z)}{A(z)}$$

Or,

$$H(z) = \frac{\sum_{i=0}^{q} b_i \cdot z^{-i}}{1 + \sum_{i=1}^{p} a_i \cdot z^{-i}} \qquad (3.1)$$

The block diagram for this may be given as follows.

$w(n)$ → [Linear causal filter $H(z)$] → $x(n) = \sum_{k=0}^{\infty} h(k) \cdot w(n-k)$

White Noise

Filter for generating random process x(n) from white noise

$x(n)$ → [Linear causal filter $1/H(z)$] → $w(n)$

White Noise

The inverse filter

Where { b_i } and { a_i } are the filter coefficients that determine the location of the zeros and poles of H(z), respectively. The random process { x(n) } uniquely represents the statistical properties of the innovations process { w(n) }, and vice versa.[26]

For the linear system with the rational system function H(z) given by Eqn. 3.1, the output x(n) is related to the input w(n) by the difference equation

$$x(n) + \sum_{k=1}^{p} a_k \cdot x(n-k) = \sum_{k=0}^{q} b_k \cdot w(n-k) \qquad (3.2)$$

1. Autoregressive Process

$b_0 = 1$, $b_k = 0$, $k > 0$.

In this case, the linear filter H(z) is an all pole filter and

the difference equation for input and output is

$$x(n) + \sum_{k=1}^{p} a_k \cdot x(n-k) = w(n)$$

2. Moving Average Process

$a_k = 0,\ k >= 1.$

In this case, the linear filter H(z) is an all zero filter and the difference equation for input and output is

$$x(n) = \sum_{k=0}^{q} b_k \cdot w(n-k) \qquad (3.3)$$

3. Autoregrassive Moving Average Process

In this case, the linear filter H(z) has both finite poles and zeros and the corresponding difference equation is given by Eqn. 3.1.

Analysis of a Time Series in Frequency Domain

To analyze a time series in frequency domain, it is necessary to transform the series into its frequency domain description. This is done by applying Fourier transform to the series. The Fourier transform of a time series z(t), is defined as follows:

$$Z(\omega) = \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} z(t) \cdot e^{-j\omega t}\, dt$$

If the time series is in discrete form, $\{z_r\}$, r = 0,1,2,...,N-1, then the discrete Fourier transform is defined as follows.

$$Z_k = \frac{1}{N} \cdot \sum_{r=0}^{N-1} z_r \cdot e^{-i(2\pi kr/N)} \qquad k = 0,1,2,\ldots,N-1$$

Data in frequency domain can be transformed into time domain using the inverse Fourier transform. This is defined as follows:

$$z(t) = \int_{-\infty}^{\infty} Z(\omega) \cdot e^{i\omega t} \, d\omega$$

Similarly, for the case of discrete data, the inverse transform is defined as follows:

$$z_r = \sum_{k=0}^{N-1} Z_k \cdot e^{i(2\pi kr/N)} \qquad r = 0,1,2,\ldots,N-1$$

i	$= \sqrt{(-1)}$
ω	= frequency
$Z(\omega)$	= Fourier transform of a continuous function $z(t)$
Z_k	= discrete Fourier transform of discrete sequence z_r
$z(t)$	= inverse Fourier transform of $Z(\omega)$
z_r	= inverse Fourier transform of Z_k

Fast Fourier Transform

Fast Fourier Transform is a computer algorithm to compute discrete Fourier transform. It works in three stages. The first stage involves partitioning the full sequence of series into a number of shorter sequences. Calculation of the discrete Fourier transform of these smaller sequences is carried out conventionally in second stage. And finally, the Forier transform of these shorter sequences are combined in the third stage to yield the full discrete Fourier transform of the original series.[25]

As described in Chapter 1, the diagnostic system should respond fast and its calibration should be easy. Filters like autocorrelation and higher order autoregressive and moving average processes may be capable of interpreting data more accurately but they suffer the drawback of being slow in response as they involve more complex mathematical calculations [12]. Also, low order moving average

processes have been found to be capable of representing the system satisfactorily after removal of deterministic components from the signal [10,12]. The vibration signal is largely dependent on the system hardware apart from the cutting mechanism. Because of this, the frequency distribution of vibration signal does not change appreciably for different cutting conditions. This is confirmed during preliminary data processing, as will be seen in Chapter 4. Because of reasons mentioned above, moving average process has been chosen for the present work.

Chapter 4

Diagnostics of a Peripheral Milling Process

4.1 Selection of Measuring Parameters

A diagnostic system must disclose improper performance of a machining process and identify its cause reliably. To meet this very important requirement, the suitable elements of vector $\underset{\sim}{x}$ (vector of measurable parameters characterizing a milling process) have to be selected carefully before the actual design of the hardware of the system. They should contain complete information about the process, should be available for monitoring with simple and reliable sensors in industrial conditions and should be resistant to contamination by noise. Moreover, the total number of these elements should be least but sufficient. This requirement can be explained as follows:

Let us assume that the convex sets X_{F1}, X_{F2} ,..., X_{Fn} contain values of vector $\underset{\sim}{x}$ in case of the faults #1, #2, ..., #n respectively. Generally,

$$X_{Fi} \cap X_{Fj} \neq 0 \ . \qquad (4.1)$$

It means that the same vector $\underset{\sim}{x}(t)$ could belong to several sets X_{Fi} simultaneously. So, elements of $\underset{\sim}{x}$ must be selected in such a way that the identity of any pair of sets of X_{Fi} and X_{Fj}, should be avoided and each set X_{Fi} should differ from the set of $[X_y \cap X_z]$. Only fulfillment of these conditions allows us to distinguish the fault #i from the fault #j . Some important aspects about how to extract appropriate measured signals of the elements of X_{Fi} which are contaminated by noise have been discussed by Zakovorotny, Ladnik and Dhande [9]. Procedure for identification of the most noise-proof

frequency ranges of elements X_{Fi} using the coherence function between the force signal from the cutting zone and the elements X_{Fi} was suggested by these investigators. Calculation of the coherence function values allows us to compare different measurable parameters from the viewpoint of their noise resistance while selecting elements of $\underset{\sim}{x}$. For the selected vector $\underset{\sim}{x}$, the sets of X_y, X_z and X_{Fi} have to be obtained on the basis of appropriate experimental data and theoretical considerations at the time of tuning of a diagnostic system. The sets in x-domain which correspond to different states of a machining process are presented in the form of particular rules related with the threshold values.

To establish these rules and thresholds, it is necessary to do the following:

-to analyze the sets Y and Z and their transformation into x-domain by operators G_y and G_z, and

-to investigate the experimental data for studying the relations between the actual performance of a machining process and the values of vector $\underset{\sim}{x}(t)$.

The following are the most frequently occurred faults during a milling process.

- Tooth/teeth breakage/chipping,
- Eccentricity of a cutter itself and/or mechanism of a cutter holder,
- Key failure,
- Wear,
- Chatter,
- Built-up edge,
- High cutting edge temperature etc.

All these faults have one common point, namely, non-uniform conditions of cutting for different teeth of a cutter. The non-uniformity is caused by different thicknesses of uncut chip for different teeth when they locate at the same position with respect to workpiece. The cutting force affected by this phenomenon causes, in its turn, non-uniform vibrations of the machine-workpiece structure. That is why the main objective of the present work is to suggest simple and reliable numerical procedures which allow a diagnostic system to observe automatically different non-uniformities with respect to teeth and subsequently identify their cause, i.e. the fault. A very important requirement of these numerical procedures is their suitability for on-line operation

As a source of diagnostic signal, acceleration of vibratory motion of a workpeice in vertical direction has been chosen . This signal can be sensed easily in relatively wide frequency range. Accelerometers with magnetic bed can be mounted directly upon a workpiece because machining is being performed without any cutting fluid. During cutting operation, vibrations of workpiece are caused mainly by the change in cutting force which is often used as a diagnostic signal [10,12]. The choice of the type of the parameter selected for measurement and its form is important. So, the selected source of diagnostic information about the machining process satisfies all basic requirements to such a signal given in Section 3.1. Therefore, in our investigation, we confined ourselves with only one measured signal, i.e. vector $\mathbf{x}(t)$ is reduced to a scalar $x(t)$.

4.2 Experimental Set-Up

The block diagram of the experimental setup is given in

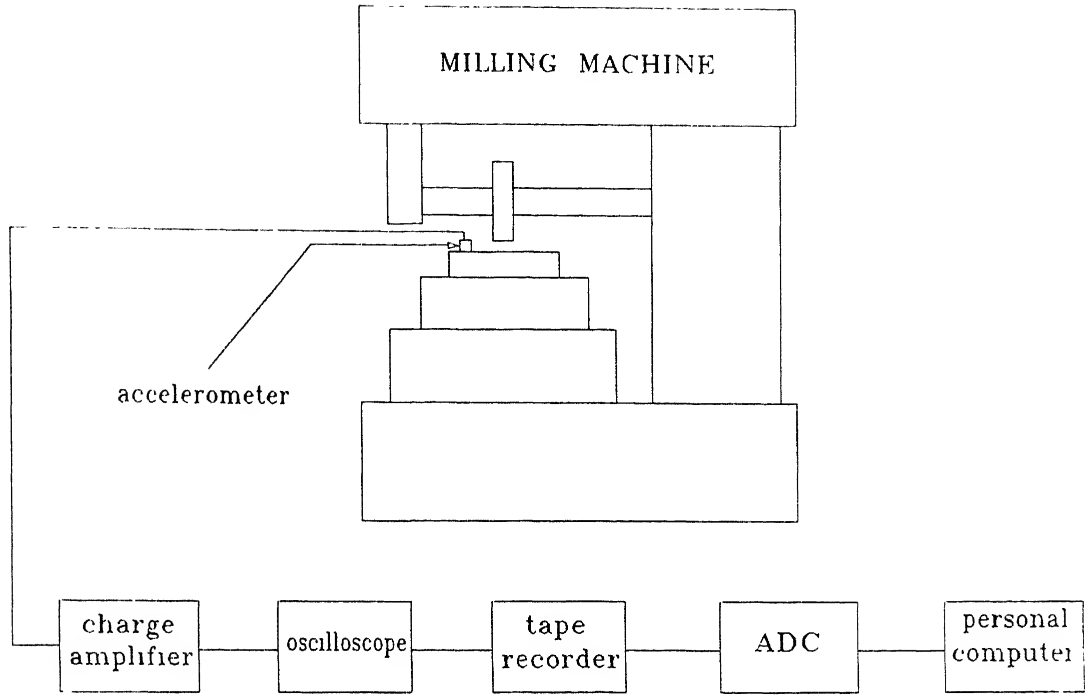
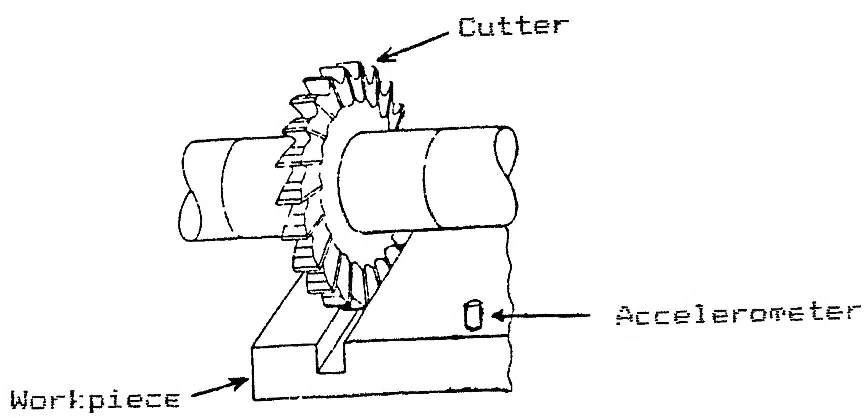
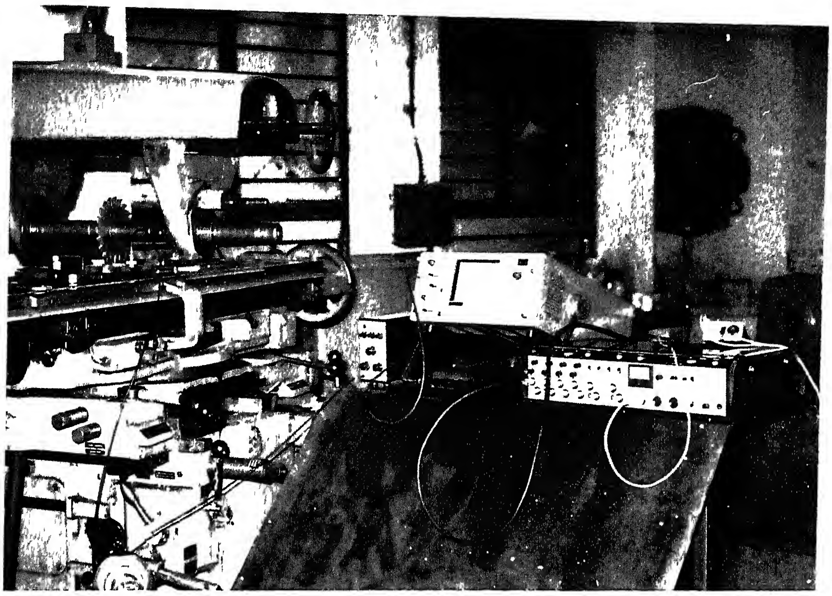


Fig.4.1(a) Block Diagram of Experimental Set-Up



(b) Schemetic Diagram of Cutter, Workpiece and Accelerometer

Fig.4.1 Experimental Set-Up



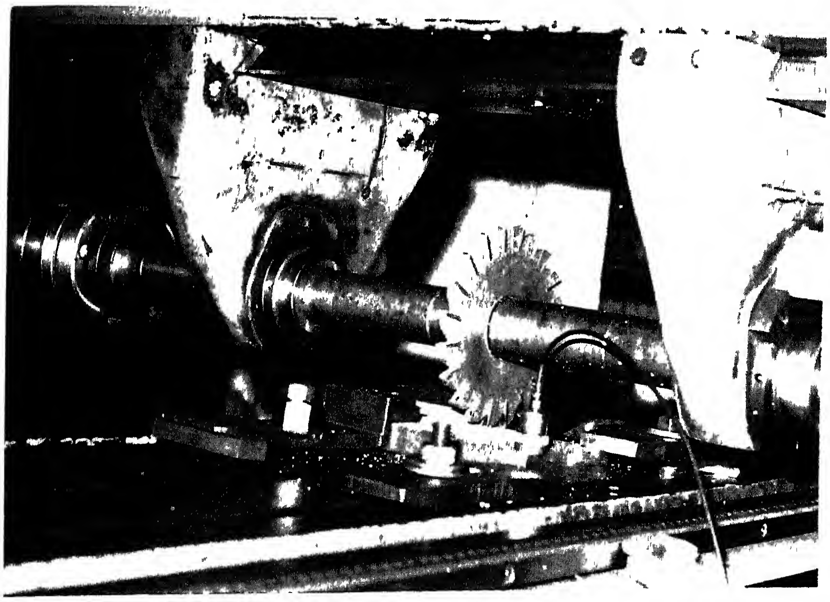


Fig.4.1(c) Photographs of Experimental Set-Up

Fig.4.1(a). Figure 4.1(b) is a schematic illustration of relative positions of cutter workpiece and accelerometer. The photographs of experimental set-up are given in Fig.4.1(c). The experimental setup includes the milling machine, a piezo-electric accelerometer, a charge amplifier, an oscilloscope, a tape recorder etc. Each of these components of the experimental setup has been briefly introduced in the Appendix. A horizontal spindle universal milling machine has been used for experiments. A side and face cutter (High Speed Steel) with 152.4 mm (6") outer diameter, 6.35 mm (1/4") width and 31.75mm($1^1/_4$") bore has been used for cutting. A piezo-electric accelerometer with magnetic bed is used to pick up the vibration signal from the work piece. The work piece is a mild steel flat (200 mm x 150 mm x 20 mm). The accelerometer has been placed on the workpiece in the vertical position to sense the vertical vibrations of the workpiece. This signal has been amplified in the charge amplifier. The lower limit of frequency is set to 10 Hz to avoid low frequency noise. Preliminary experiments revealed that the signal did not have significant frequency component beyond 3kHz. Therefore, it was decided to keep higher frequency limit to 3kHz. The output of the charge amplifier is fed to the digital storage oscilloscope which has been used to visualize the signal. While recording, the signal is directly sent to the tape recorder from the amplifier.

Signals have been recorded for different rotational speeds and different feed rates. The RPM has been kept at 50, 63, 80 and 100 and for each RPM, the feed rate has been varied as 19, 24, 30 and 38 mm/min. This recorded signal is then digitized with an analog-to-digital converter (ADC) at different sampling rates keeping the digitization synchronized with the rotational speeds. The tape

recorder used for the purpose was capable of recording four signals simultaneously, facilitating the sensing of the signal at four different locations at the same time if desired.

4.3 Preliminary Data Processing

It is essential to digitize the data for proposed method for signal processing. In the present case, the vibration signal is in the analog form and has been converted to digital form using an analog to digital converter. While digitizing we face with the following restrictions:

1. Limited frequency range.
2. Limited resolution with respect to the frequency.
3. Limited resolution with respect to the magnitude.

The frequency range of the sensed signal is already limited by the bandwidth of the sensor and the threshold settings of the charge amplifier. Furthermore, while sampling, the frequency components higher than a particular limit are lost. The highest frequency, which can be sampled, is given by the following expression,[22]

$$F_N = 1/(2\cdot\Delta t) \tag{4.2}$$

where, Δt is the sampling interval. Furthermore, Δt can be split into two parts,

$$\Delta t = \Delta t_1 + \Delta t_2 \tag{4.3}$$

where Δt_1 is the time required to update the data register of the ADC and to report the completion of this operation to the computer, Δt_2 is duration of execution of the software for reading new datum and putting it in a particular computer memory cell. While sampling, we can acquire data within the frequency range of zero to F_N. From Eqn.4.2, it is obvious that Δt has to be reduced for higher values of

F_N. The first component, Δt_1, depends on the system hardware and cannot be changed. To reduce Δt_2, program for preliminary data processing should be written in assembly language. The data should be stored first in the computer memory. When the inputting of data is completed, the program should put an integer data array, from the memory, in a particular file on the output device (e.g. floppy, computer hard disc etc.). Resolution ability of sampling procedure in frequency domain can be calculated with the following expression:

$$b = 1/(N \cdot \Delta t) \qquad (4.4)$$

where N is total number of the samples. From Eqn.4.4, it is evident that larger resolution (i.e. smaller b) corresponds to larger length of the record. We assume that Δt will be decided by a desirable value of the sampling frequency (F_N). The resolution ability can also be increased by larger value of Δt but in that case F_N may be adversely affected.

The output of the ADC is a sequence of bytes. The number of active bits in the output of the ADC depends on the number of hardware channels of ADC. If this number is equal to p, then the magnitude range of the ADC output will be defined by 2^p. Thus the total range of an analog input signal can be split into 2^p equal units, which is known as resolution with respect to amplitude.

Using the Signal Analyzer, it was found that the signals recorded at different cutting conditions did not have any spectacular difference in frequency distribution. All signals had peaks at the same frequencies which were mainly 23.42, 41.97, 63.44, and 84.91Hz. Because of this, the basis for further investigation has been kept to be the amplitude of the signal only. Characteristics of the signal have also been studied with different locations of the sensor,

different work pieces, different cutters, different locations of the hanger bearing etc but the basic tendency of the change in amplitude has remained the same. This observation further establishes the convenience and reliability of the amplitude study for the detection of eccentricity.

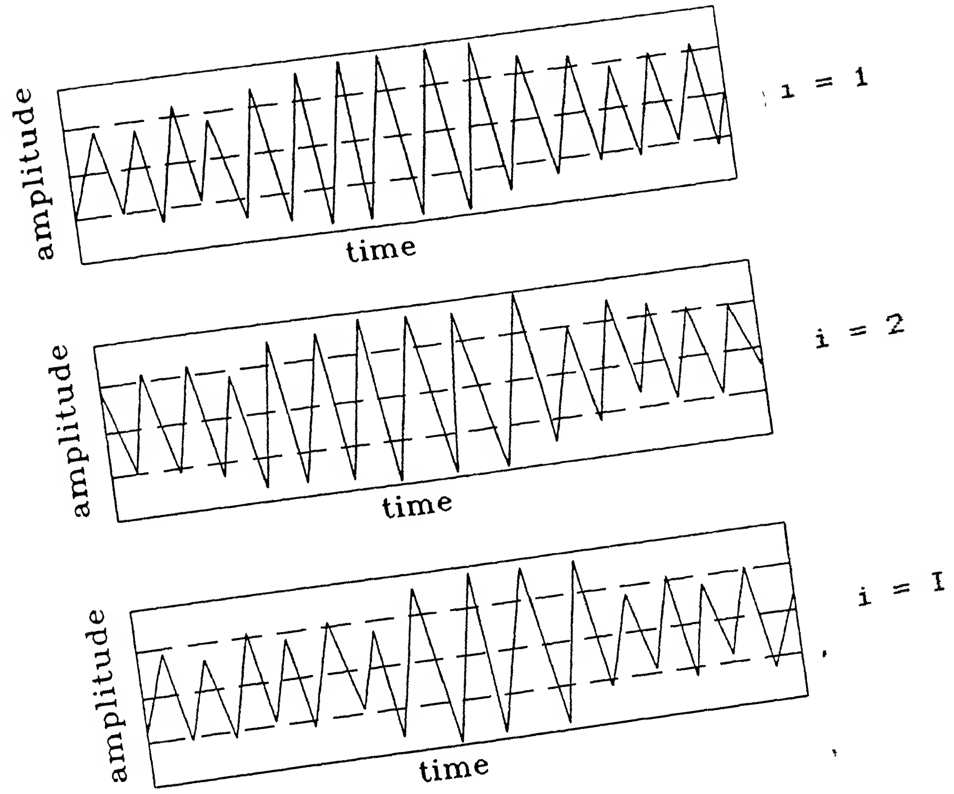
4.4 Processing of Experimental Data

As it was said earlier, it is important to reveal the possible non-uniformities in the cutting conditions for different cutting teeth of a cutter. To achieve this the following data processing procedures have been carried out. The recorded time sequences (without entry and exit) were split up into the intervals corresponding to one revolution of the cutter (index "i" denotes the number of a particular revolution). It was done based on the magnitudes of the angular velocities of the spindle and the time increment Δt. Let us denote each element of a particular record as x_{ij}, where i is the particular number of revolution and j is the particular number of the element within the i-th revolution, i=1,2,3...,I; j=1,2,3,...,J for each record. In order to reveal non-uniformities in the data for different teeth, the envelope curve for the signal x can be obtained as follows:

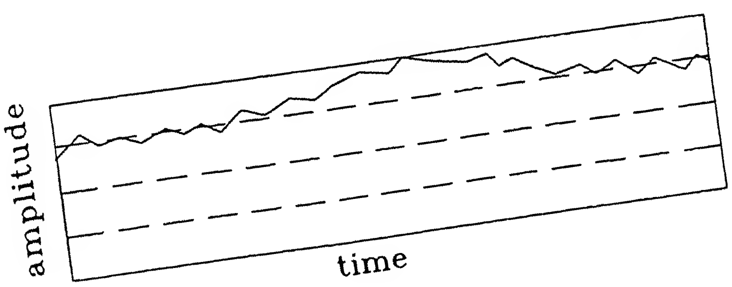
$$x_j^E = (1/I) \cdot \sum_{i=1}^{I} |x_{ij}| \quad , \qquad (4.5)$$

where j = 1,2,3,...,J.

Effect of Eqn.4.5 can be explained using a diagram given in Fig.4.2. Physically, it is nothing but averaging of the values corresponding to the same angular situation of a cutter. Absolute values are taken to obtain only one envelop curve. This curve highlights the regular changes in the vibratory motion of a workpiece



Different Samples of a Data



Processed Data

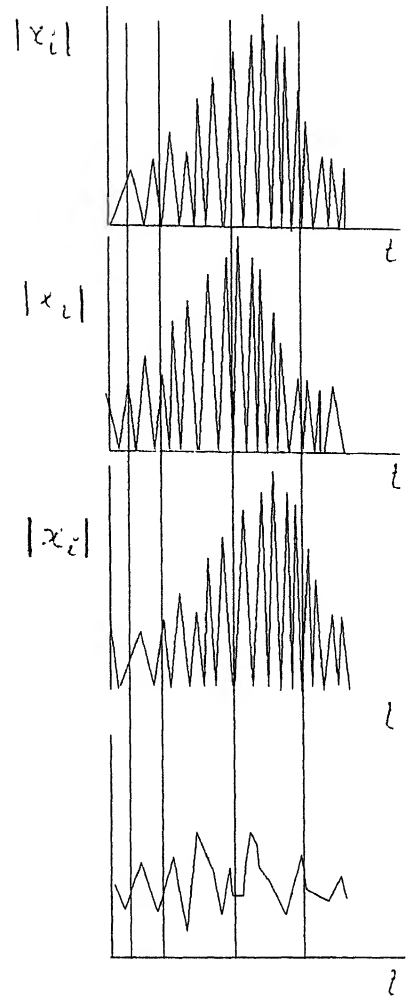
Fig.4.2 Illustration of Effect of Processing With Equation 4.5

during one revolution of a cutter and, therefore, permits us to identify differences in cutting conditions for the teeth. Eqn.4.5 contain only fast operations of summation and obtaining of absolute values. Computational time can be further reduced by selecting $I=2^{l}$, where l is integer. In this case a division operation is reduced to a simple shifting of a binary word containing the result of summation of the absolute values on l bits to the right hand side. But direct application of Eqn.4.5 to the magnitude of experimental data does not give us a desirable result due to presence of high frequency components. This leads to correspondence of same point, j, to peaks in some revolutions and valleies in other which disables the system to produce the magnitude variation correctly. The diagram for this case is given in Fig.4.3.

Application of low-pass filtering procedure to the magnitude of original data allows us to reduce this effect and thus considerably increase the reliability of the diagnostic system. To reduce the duration of the MA process, the latter is performed with the following recursive expression:

$$\bar{x}_{k+1} = \bar{x}_k + (1/n) \cdot (x_{k+n} - x_k) . \qquad (4.6)$$

where k is a serial number of an element of the record, n is the averaging length, $\bar{x}_k$ is the kth element of the MA series. For implementation of Eqn.4.6, it is again better to have n as some power of 2. Total length of the record x_1 should not be less than $(I \cdot J+n)$. Of course, the MA technique does not allow us to sense difference in vibrations due to changes in the cutting force acting on each tooth from its entry up to exit. But this difference becomes very less if the number of simultaneously cutting teeth is more than one. Similar averaging effect is observed when the cutter consists of helical



PROCESSING BY EQUATION

$$x_j^E = 1 \cdot I \cdot \sum_{i=1}^{I} | x_{ij} |$$

Fig 4.3 Effect of Processing Magnitude of Data With Equation 4.5

teeth. These cases embrace the most part of the practical applications.

Now, substituting elements of initial record x_{ij} by the corresponding values $\bar{x}_{ij}$ of MA(n) sequences, we obtain the expression

$$\bar{x}^{E}_{j} = (1/I)\cdot\sum_{i=1}^{I}|\bar{x}_{ij}| \quad , \qquad (4.7)$$

In order to verify the suitability of the procedure described above for diagnostic purposes, several records of output signal of accelerometer mounted on the workpiece were made for different cutting conditions.

Examples of the original record for one spindle revolution for idle regime and for cutting are given in Fig.4.4(a), 4.4(b) respectively. Amplitude of the signal is given in relative units to avoid calibration of output channel. Data processed with Eqns. 4.5, 4.6 are given in Fig.4.5 (a-g). The increment in time scale in these figures corresponds to the theoretical time interval between entry and exit of two adjacent teeth of a cutter.

From these figures it can be observed that for the milling machine and cutter under consideration, normally only 4 to 8 (i.e. I= 4 to 8) revolutions of a cutter are sufficient to obtain a smooth enough envelop curve for MA(32), i.e. $J=2^5=32$. For this particular equipment, the non-uniform cutting conditions for different teeth are quite evident.

During the cutting process, a difference in the amplitude of a signal for some teeth is as much as double and sometimes even more. For idle regimes, vibrations are practically uniform. So, the suggested procedure can reveal presence of non-uniform cutting conditions for different teeth.

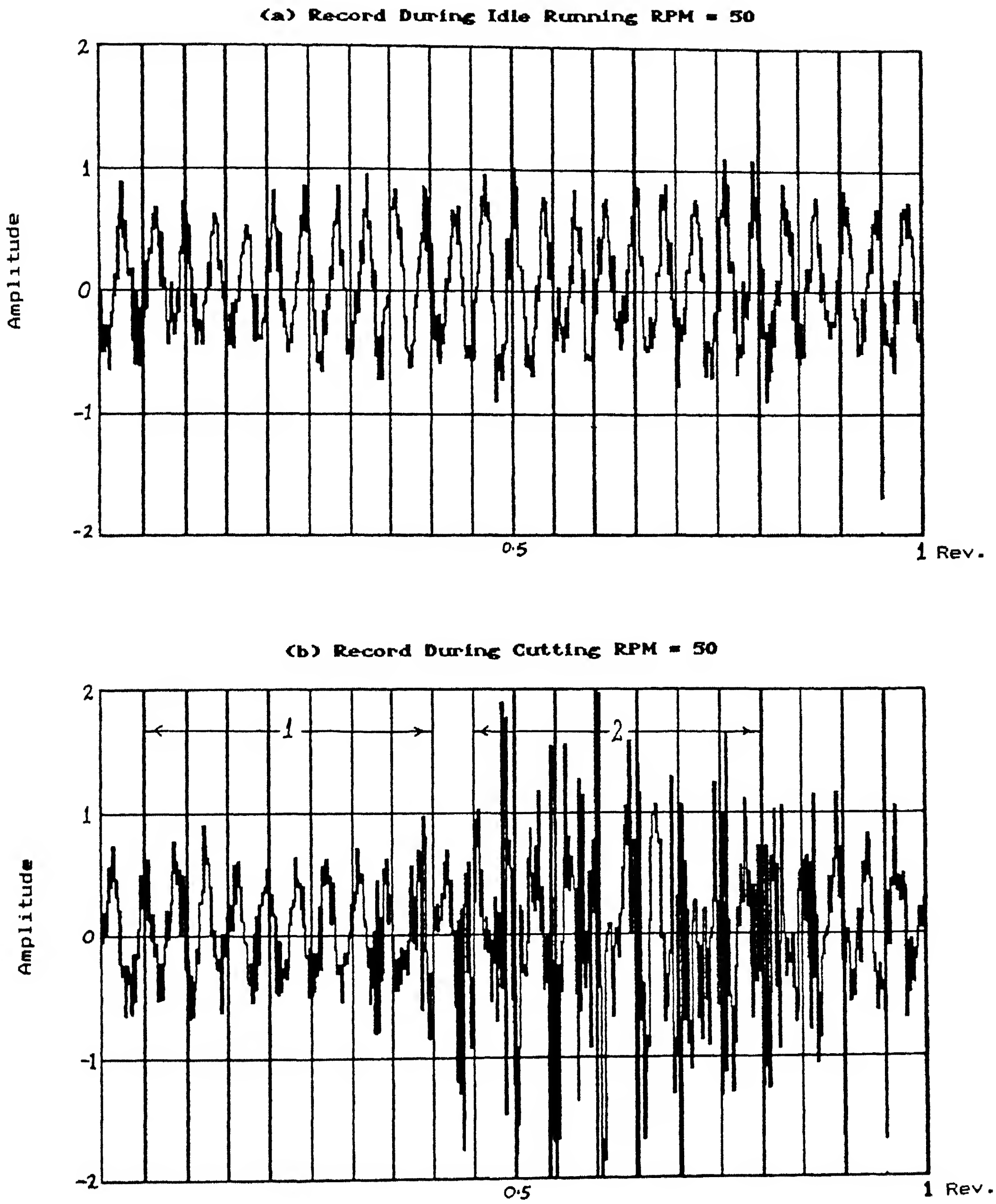


Fig.4.4 An Example of Original Record for One Revolution of the Spindle

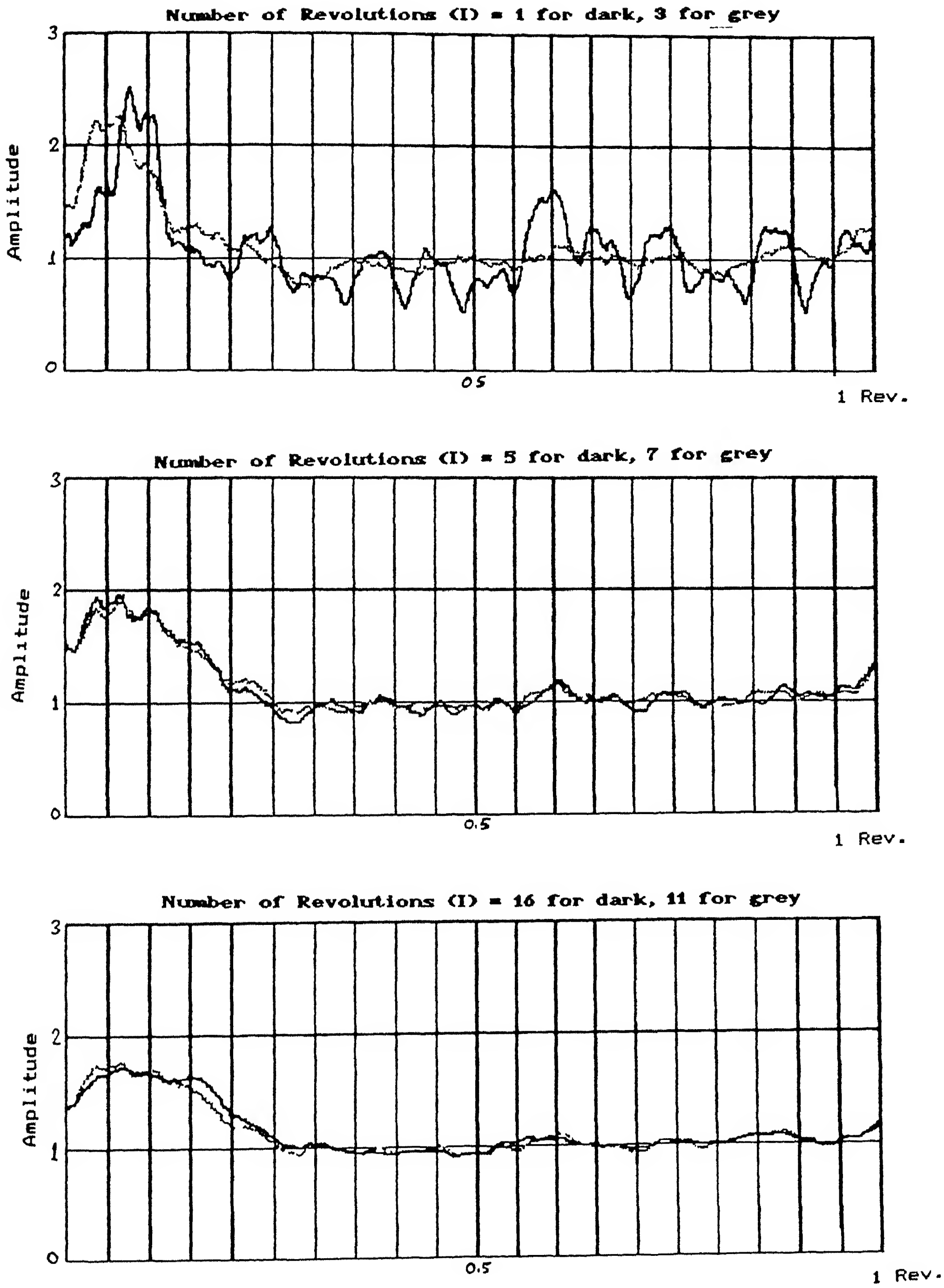


Fig.4.5 Experimental Data Processed With Equations 4.5 and 4.6

(a) Cutting, Feed Rate = 19 mm/min, RPM= 100, Averaging Length = 32

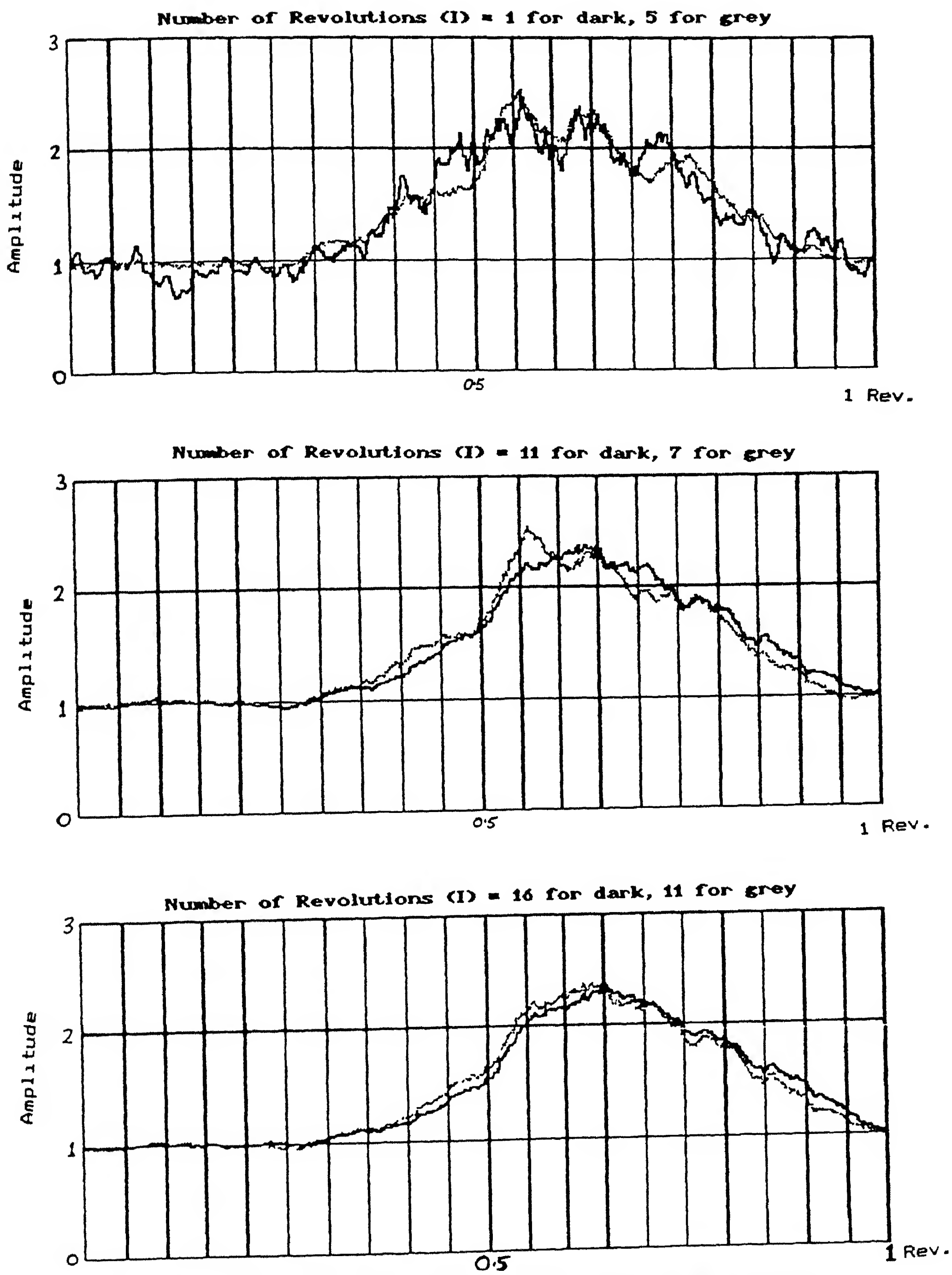


Fig.4.5 Experimental Data Processed With Equations 4.5 and 4.6
(b) Cutting, Feed Rate = 19 mm/min, RPM = 50, Averaging Length = 32

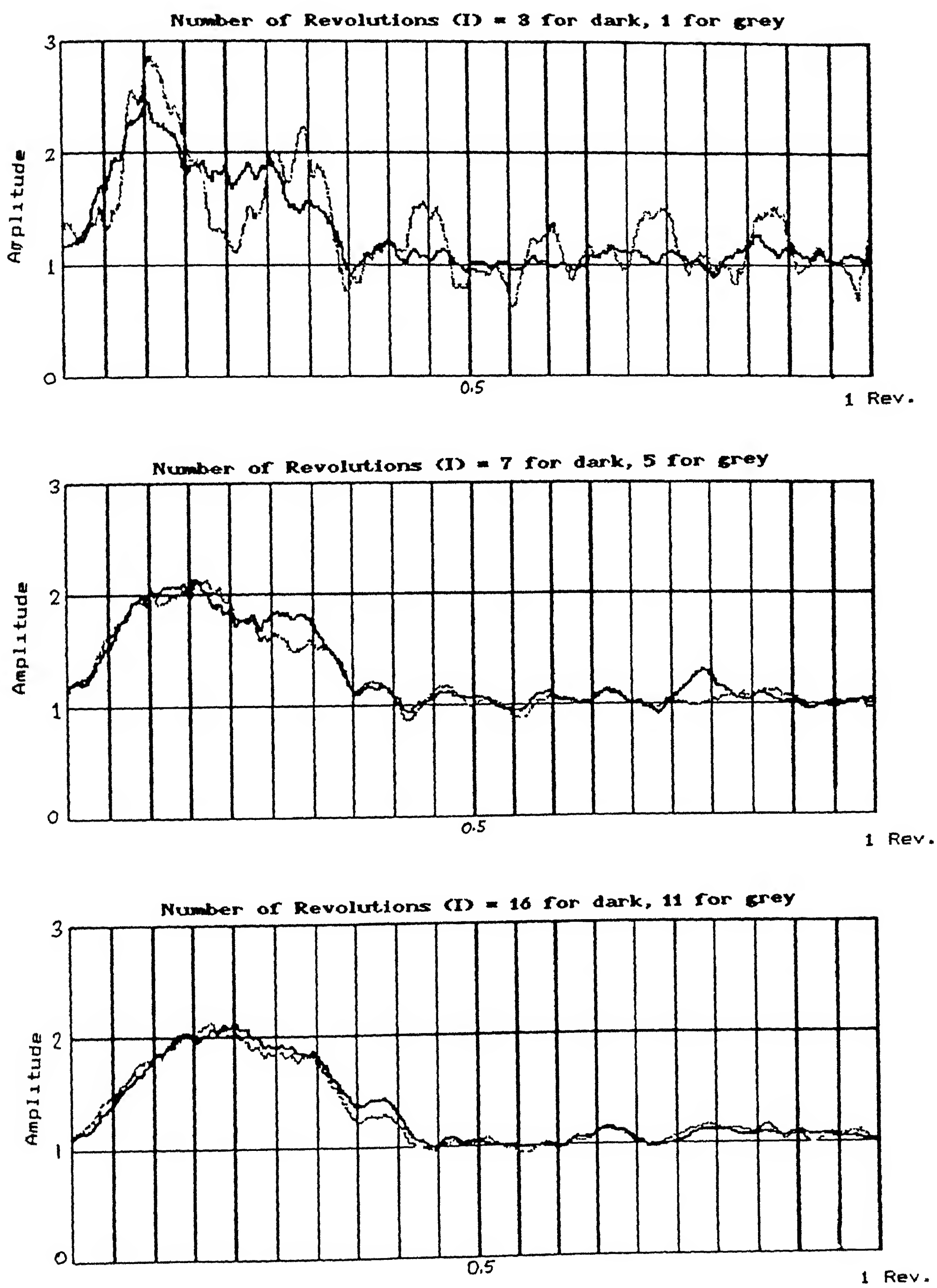


Fig.4.5 Experimental Data Processed With Equations 4.5 and 4.6
(c) Cutting, Feed Rate = 38 mm/min, RPM = 100, Averaging Length = 32

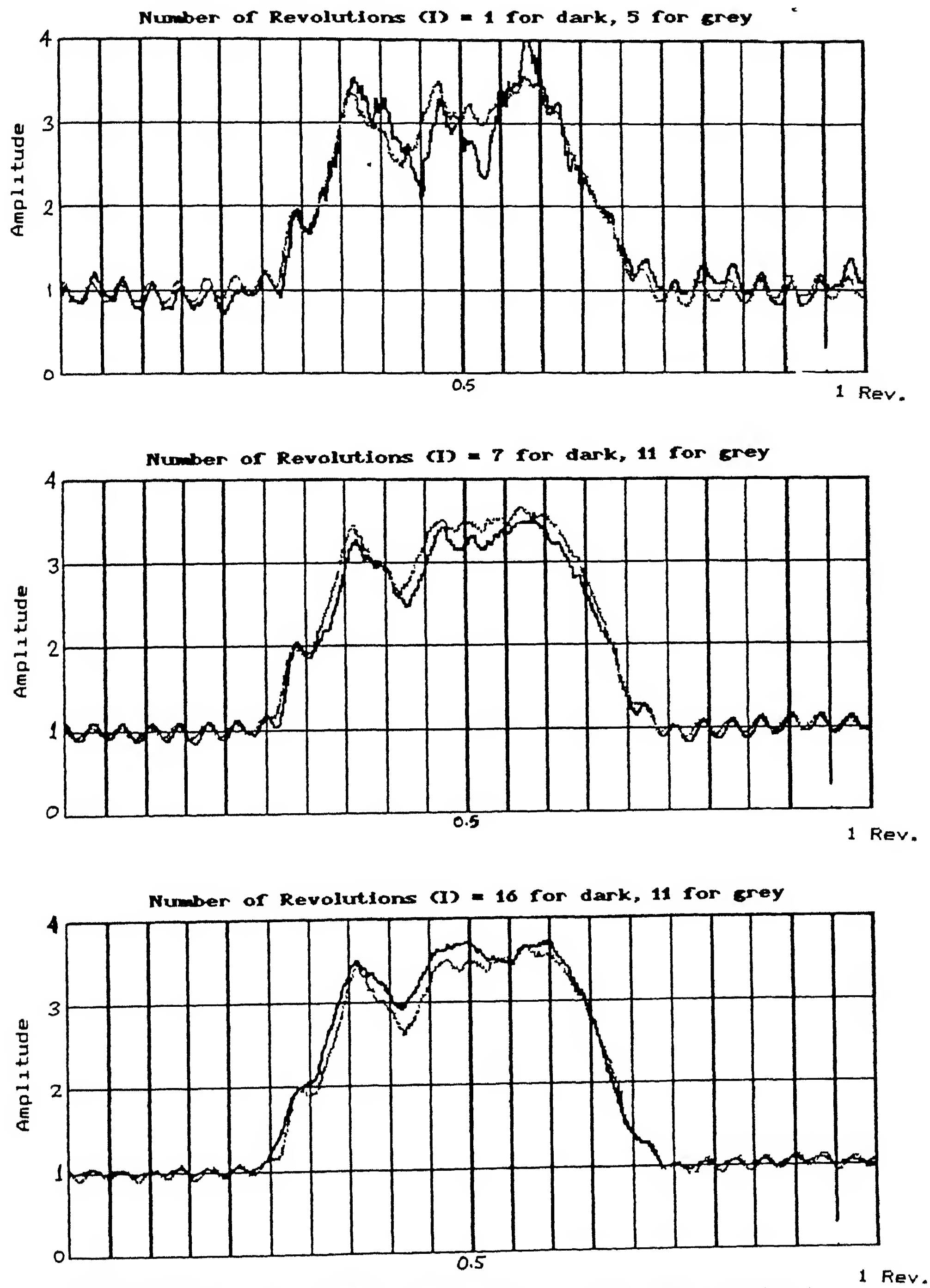


Fig.4.5 Experimental Data Processed With Equations 4.5 and 4.6
(d) Cutting, Feed Rate = 38 mm/min, RPM = 50, Averaging Length = 32

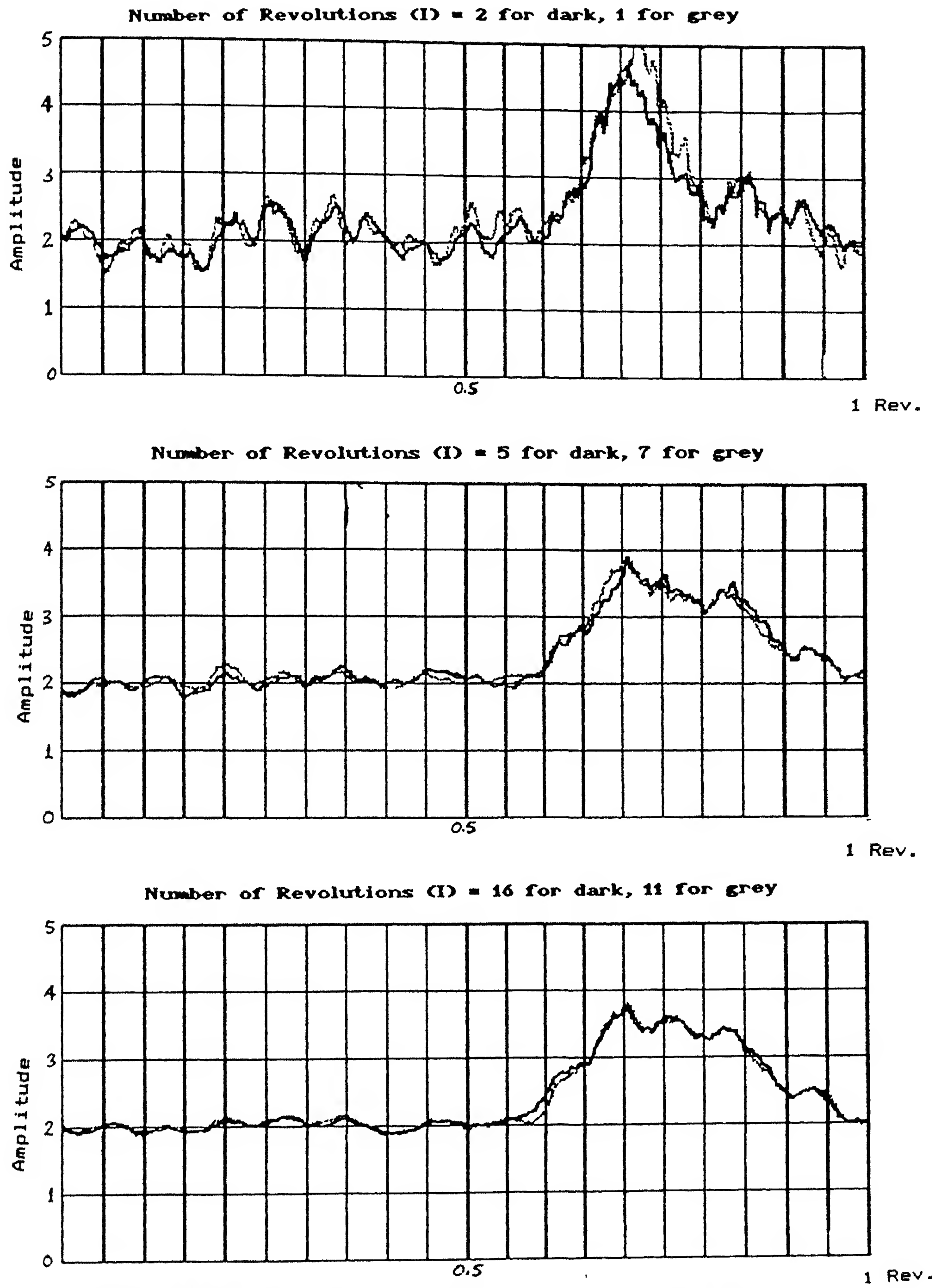


Fig.4.5 Experimental Data Processed With Equations 4.5 and 4.6
(e) Cutting, Feed Rate = 38 mm/min, RPM = 80, Averaging Length = 32

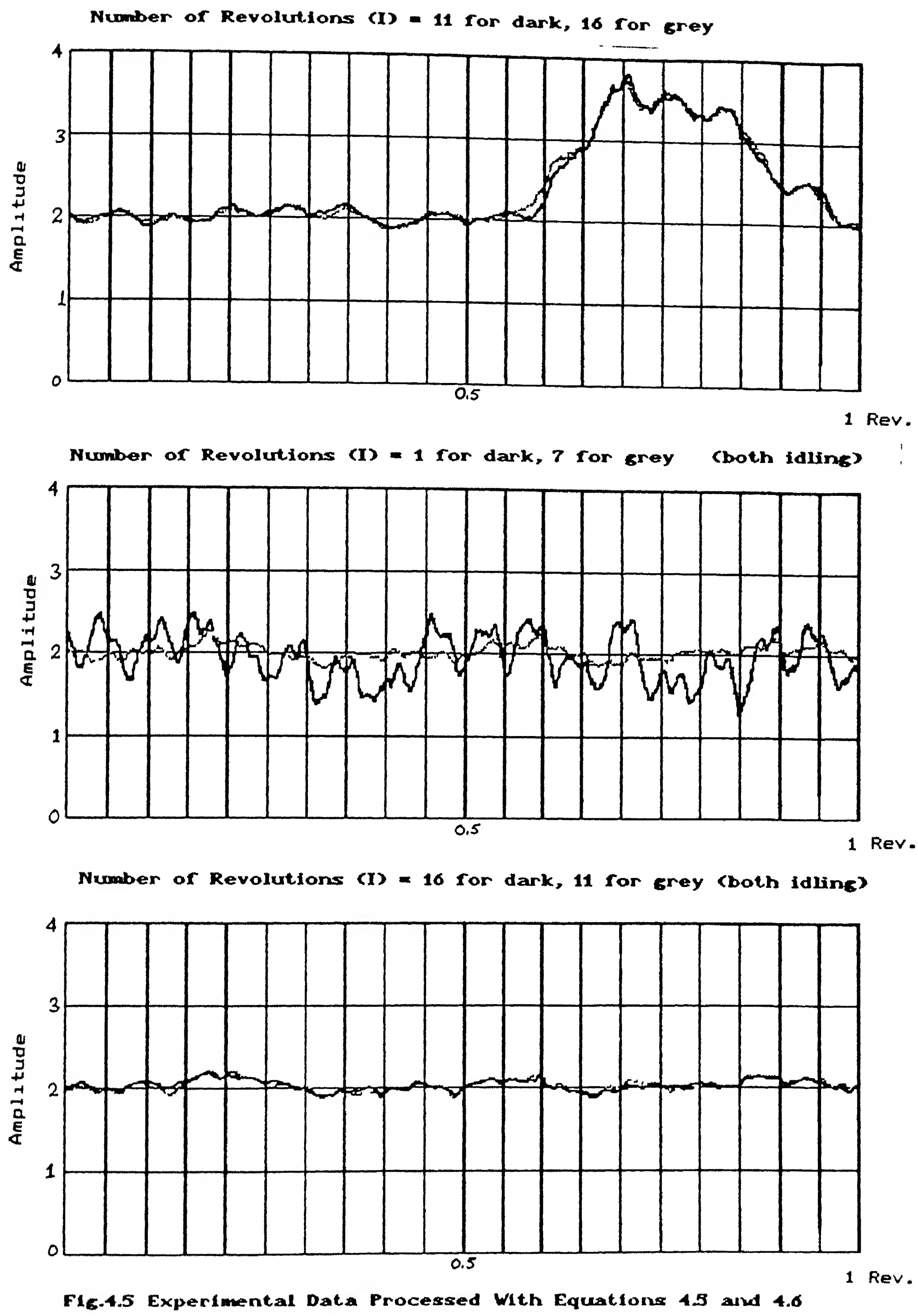


Fig.4.5 Experimental Data Processed With Equations 4.5 and 4.6
(f) Cutting, Feed Rate = 38 mm/min, RPM = 80, Averaging Length = 32

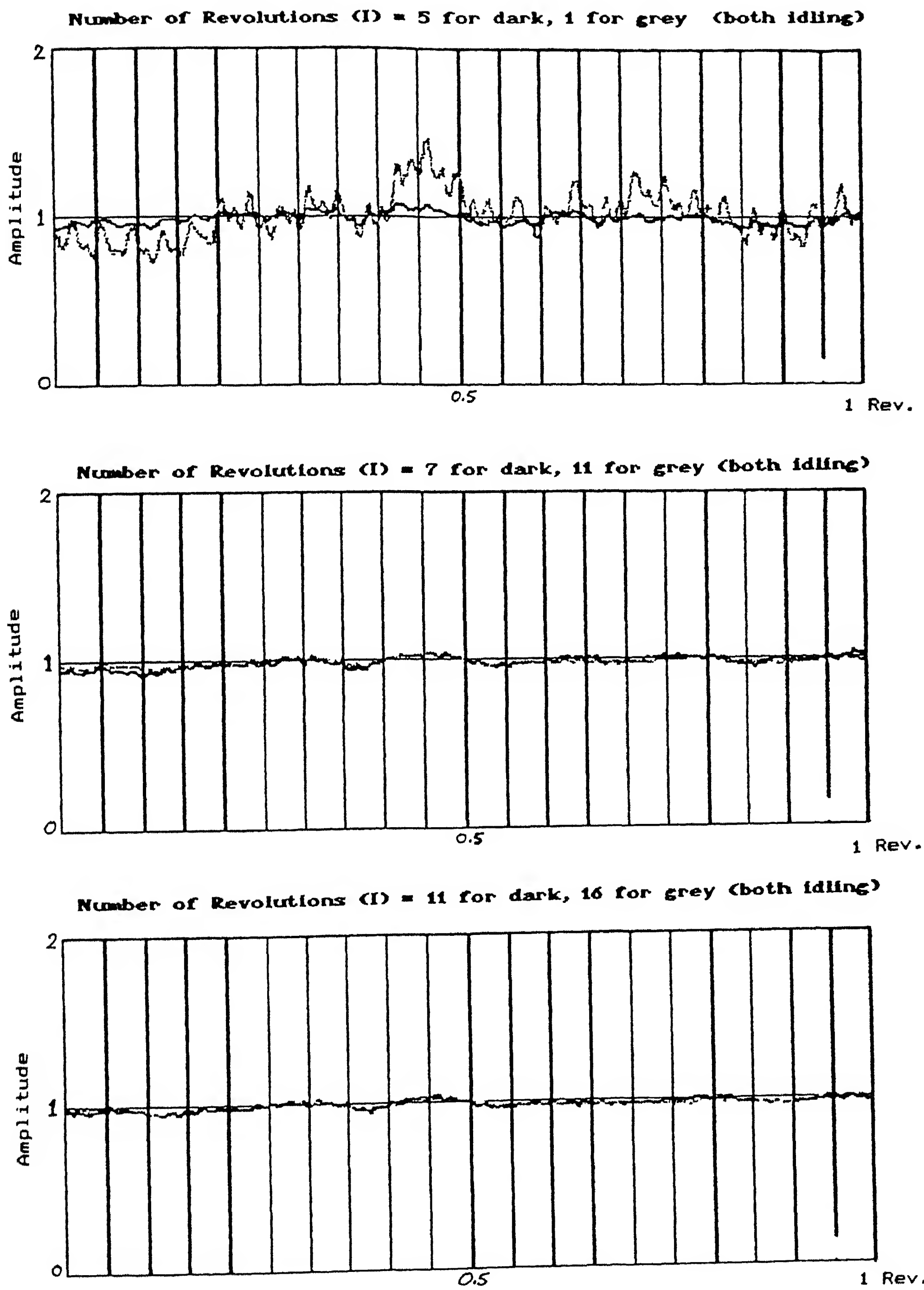


Fig.4.5 Experimental Data Processed With Equations 4.5 and 4.6
(g) Idle Running, Feed Rate = 0, RPM = 50, Averaging Length = 32

But mere detection of non-uniformities is not enough for a diagnostic system. It has to identify the cause of the phenomenon. For all curves of the original and processed data (Fig.4.4a, 4.4b, 4.5a-g) the following features can be seen:

-Curves for the machining consists of two continuous intervals of approximately equal length. One of them is characterized by relatively small and uniform amplitude of the recorded signal while the amplitude of the signal in the other interval gradually increases up to some maximum magnitude and then decreases with almost the same intensity;

-For idle regimes and for intervals with small amplitudes, the magnitudes of these amplitudes are practically equal. These features allow us to infer that for each spindle revolution, there is practically no cutting during the time interval with small amplitude. Within other interval, volume of the swept material of the workpiece gradually changes as the signal amplitude changes. This inference is confirmed by the analysis of the initial data (Fig.4.6a-c). The portion of the recorded signal during one spindle rotation with larger amplitudes has much more prominent high frequency components than the portion with smaller amplitudes. It means that within the larger amplitude interval the dynamic subsystem of a workpiece is excited by the resulting vertical component of the cutting force. This force contains high frequency components. The interaction between the dynamic subsystem of cutter and workpiece also takes place through the cutting force. So we can expect the appearance of vibrations of a workpiece on the natural frequencies of the cutter subsystem while cutting. Spectral composition of the low amplitude signal, differ from the high amplitude signal, but is very similar to the record for idle regime. So it is clear that the cutter is engaged in cutting only

during approximately one half of a revolution. During the cutting interval, the thickness of the uncut chip is gradually increasing for each next tooth and after some maximum value is reached, it is decreasing in a similar manner. The cause of such a behavior is the eccentricity of the cutter or its holder. Examination of the machine has confirmed that the arbor of the machine was in a bow-like form.

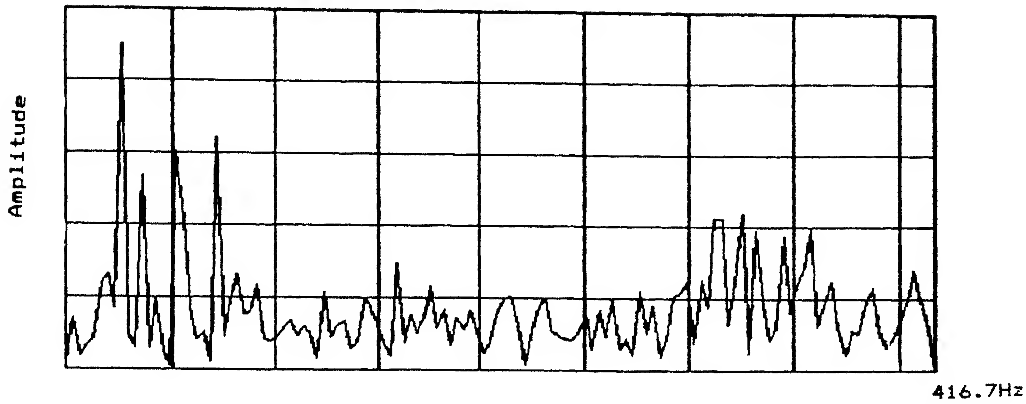
As it was shown above, the application of the MA procedure and synchronization of data with an integer number of spindle revolutions while averaging, can be used for on-line identification of the actual status of the process. This approach can be combined with the time series analysis in the frequency domain. Such an analysis is very useful for identification of two groups of factors affecting the process performance, e.g.,

(1) Appearance of sources of vibrations with different spectral compositions for the machine-workpiece dynamic system.

(2) Changes in the structure of the machine-workpiece system cause changes in its response to excitation which are reflected in the spectral characteristics of sensing parameter(s) $x(t)$, or the combination of these two factors, (1) and (2).

Combination of data processing in the time and frequency domains for the process status recognition, means splitting continuous time series of the vectors $\underset{\sim}{x}(t)$ elements in different intervals using the time domain operations and obtaining the spectral characteristics of these intervals separately for further analysis. The Fourier transforms of original time signatures of different time intervals are presented in Fig.4.6(a-c). The Fourier transform of the time series of the record for idle regime (Fig.4.4a) is depicted in Fig.4.6(a) while Fourier transform for intervals 1 and 2 (Fig.4.4b) are shown in

(c) Fourier Transform of a High-Amplitude Interval in a Signal Received During Cutting RPM = 50



(b) Fourier Transform of a Low-Amplitude Interval in a Signal Received During Cutting RPM = 50

(a) Fourier Transform of a Signal Received During Idle Running RPM = 50

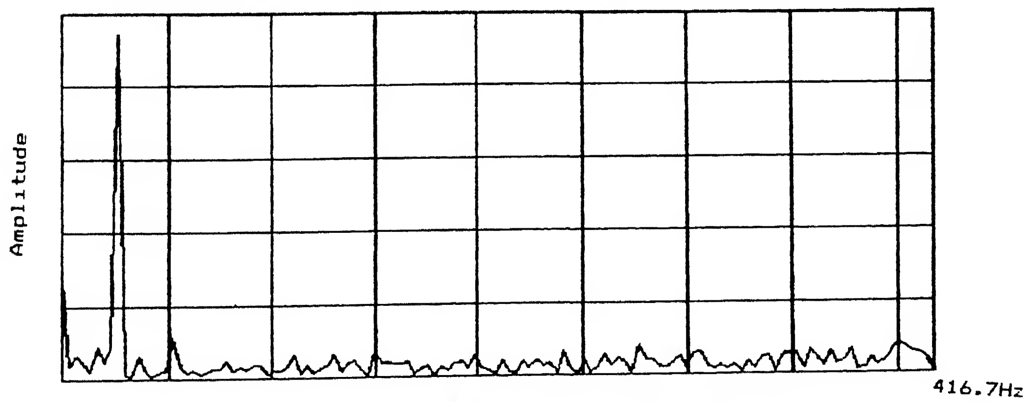


Fig.4.6 Fourier Transforms of the Original Record

Chapter 5

Conclusions

This chapter discusses effects of various aspects of peripheral milling process on the vibration signal of the workpiece. This knowledge is necessary to design algorithms for identification of several states of the process. The possible future extension of the work have been discussed at the last.

5.1 Identification of Some Important States of a Peripheral Milling Process

The rules for denotion of several sets in the x-domain description of particular states of the milling process are formulated below considering $x(t)$ as a time series of the acceleration of the vertical motion of the workpiece.

Idle Motion

Magnitude of $\overline{x}^{E}_{j}$ (Eqn.4.7) is constant and relatively small (Fig.4.4a)for all j (throughout the revolution). Vibrations mainly constitute the natural frequencies of the workpiece dynamic subsystem. Weak vibrations constituting the natural frequencies of the cutter (spindle) dynamic subsystem are also possible due to the link of the two subsystem through the housing, hanger and machine bed.

Normal Cutting

Magnitude of $\overline{x}^{E}_{j}$ is constant and relatively large for all j. Level of the average value of $\overline{x}^{E}_{j}$ corresponds to actual depth of cut which remains constant. Vibrations take place:

-On the frequency of the cutter angular velocity and on its higher modes with successively decreasing amplitudes,

-On the natural frequencies of both the workpiece and the cutter dynamic subsystems.

Eccentricity

Gradual changes in values of $\overline{x}^{E}_{j}$ take place within one revolution (Fig.4.4b). Magnitude of $\overline{x}^{E}_{j}$ corresponds to current depth of cut. Eccentricity rate could be estimated by comparison of the minimum and the maximum magnitude of $\overline{x}^{E}_{j}$. Larger difference between the minimum and the maximum values of $\overline{x}^{E}_{j}$ corresponds to a larger value of eccentricity. Actual value of the current depth of cut can be evaluated by comparing values of $\overline{x}^{E}_{j}$ for cutting with eccentricity for idle regime and normal cutting with different depth of cut. Spectral analysis of intervals with small and with large amplitude of the original signal permits a diagnostic system to distinguish intervals with cutting from those without cutting.

Tooth Breakage

This is characterized by the following phenomena:

(1) A rapid change in magnitude of the cutting force before and during the time of the breakage may take place.

(2) For a damaged tooth, a successive revolution may produce no cutting force if the tooth is completely broken. Alternatively, the successive revolution may even produce a higher cutting force if the tooth has been partially damaged and chipped away.

(3) There could be a presence of a much-larger-than-normal thickness of the uncut chip for the tooth, next to the broken one, for the same angular position, and, therefore, a much higher value of the cutting force may be acting on this tooth. Due to this effect the breakage of teeth following the broken one is possible.

All these phenomena result in substantial changes in the cutting

force acting on the damaged tooth and the following one. But vibrations of a workpiece reflect the resultant force from all teeth engaged in cutting. Thus with the increase in the number of simultaneously-cutting teeth, k, the effect of tooth failure on the sensing acceleration of vertical vibratory motion of the work piece is getting less. So if $k=1$ then it is possible to detect tooth breakage by comparing the magnitude of the instantaneous acceleration signal $x(t)$ with threshold values obtained during a trial cut. Before the failure, the instantaneous signal rapidly increases and hits a threshold value. Then, a no-cutting interval appears before the entry of the following tooth . This tooth experiences a much higher load as mentioned. Therefore, the vertical component of the force acting on a workpiece and subsequently acceleration of vibrations are larger. The changes in the sensing signal, as described here, are symptoms of the tool failure.

When $k>1$ and in case of chipping of a tooth, it could be difficult to identify the tooth failure immediately after the event. For $k>1$, the effect of the failure in the resultant cutting force is hidden by the deposits from normal teeth, and chipped teeth can be engaged in cutting after the damage appearance and produces a force even larger than the normal one. In these situations, the tooth failure can be detected by identification of non-uniformity in cutting conditions for different teeth using Eqn. 4.5 and 4.6. The cutting due to broken tooth can be clearly observed from the values of $\overline{x}^E_j$ during the cutter revolution after tooth failure.

Tool Wear

As it was shown above,the workpeice vibrations are caused by the cutting force. The envelope curves obtained using Eqn. 4.5 and 4.6 can

be used for estimation of the average force acting on each tooth while cutting. Therefore, it is possible to calculate total time of cutting for each tooth and evaluate its wear rate taking into account its actual cutting conditions.

For a successful performance of all diagnostic operations described above, it is required to synchronize the time series of sensed with the actual angular position of the cutter. The simplest manner in which it can be done is by marking each revolution by an impulse. The impulse may be made by a simple arrangement attached to the spindle. Several such impulses could also be emitted within one revolution after displacement of a cutter on a particular angular increment. Using these impulses the uniformity of spindle rotation can be estimated apart from the synchronization of data.

Using the rules described above and threshold values obtained from trial cuts, actual sensing data can be classified as per the X-sets of idle regime, normal desirable cutting and several faults such as eccentricity, breakage/chipping of a tooth and larger then the permissible wear rate.

5.3 Proposals for Future Work

The proposed algorithm can be extended to detect tooth breakage and wear coupled with eccentricity. This can be done by observing shift of locations of pole zero, obtained by time series, in the unit circle. The algorithm can also be modified to serve as machine acceptance test. Though,the algorithm has not been designed to take into account the cutting transients like entry, exit, cutting through slot or step etc, but again with a little more experimental data and modification in the algorithm, these can also be taken into account. Similar algorithm can also be designed to detect side runout of cutter

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APPENDIX

MILLING MACHINE

Type:	M3U, Hindustan Machine Tools	
Table Size	1600 mm X 355 mm	
Power Operated Traverses:		
Longitudinal	900 mm	
Cross	300 mm	
Vertical	415 mm	
Swivel of Table (each side)	45°	
Numbers of RPM's	18	
Number of Feeds (All Directions)	18 each	
Ranges of Feed Rates:		
Longitudinal and Cross	10-480 mm/min	
Vertical	7.5-360mm/min	
Power Required:		
Main Motor	7.5 kW	(10 HP)
Coolant Motor	0.1 kW	(0.13 HP)
Rapid Traverse Motor	1.0 kW	(1.3HP)
Space Requirement	3000 mm X 2300mm	
Weight	4600 kG	

CUTTER

Type	Side Milling Cutter	
Material	High Speed Steel	
Number of Teeth	20	
Outer Diameter	152.4 mm	(6")
Arbor Size	31.75 mm	(1.25")
Width	6.35 mm	(0.25")

ACCELEROMETER

Reference Sensitivity at 50 Hz, 100 m/s^2 and 23^o C :

Charge Sensitivity	0.110pc/ms^{-2} or 1.08 pc/g
Voltage Sensitivity	0.180 mv/ms^{-2} or 184 mv/g
Undamped Natural Frequency	118 KHz
Mounted Resonance Frequency	85 KHz

Maximum Transverse Sensitivity

(at 30 Hz, 100 m/s^2) 2.2 %

CHARGE AMPLIFIER

High Sensitivity upto	10v/pc
Low and High Frequency Limits:	
f_{min}	1 , 10 Hz for acceleration
f_{max}	100 KHz
Amplification	0.1 - 100 mv per unit output
Transducer Sensitivity	0.1 - 1 or 1 - 11 pc/(m/s^2)
Used Sensitivity	1.10 pc/(m/s^2)

Digital Storage Oscilloscope (DSO)

- The GPIB (IEE 488) and RS(423 (RS-232) interfaces, allowing control by a computer.
- GPIB and RS 423 settings can be stored in battery-backed memory.
- Maximum Sampling Rate : 100 Ms/sec
- Maximum Frequency Range : 100 M Hz

Tape Recorder

Make Bruel & Kjaer Type 7005

Tape	6.35 mm instrumentation grade magnetic tape
Tape Speeds	38.1 mm/sec and 381 mm/sec
Record Reproduce Heads	4-track record reproduce heads, track geometry compatible with ISO 3413-1975
Record Leve Meter Moving	coil type, indicates maximum record and reproduce level and battery supply status
Tape Counter	3-digit counter indicating tape length in meters, selectable zero-stop
Memo-announcement	Voice microphone MM0021 for recording comments
Power Requirment	Plug-in battery pack of six batteries or plug-in power supply ZG 0199
Fast Forward and Rewind Time	7 min for 690 m of tape 2 sec for stopping.